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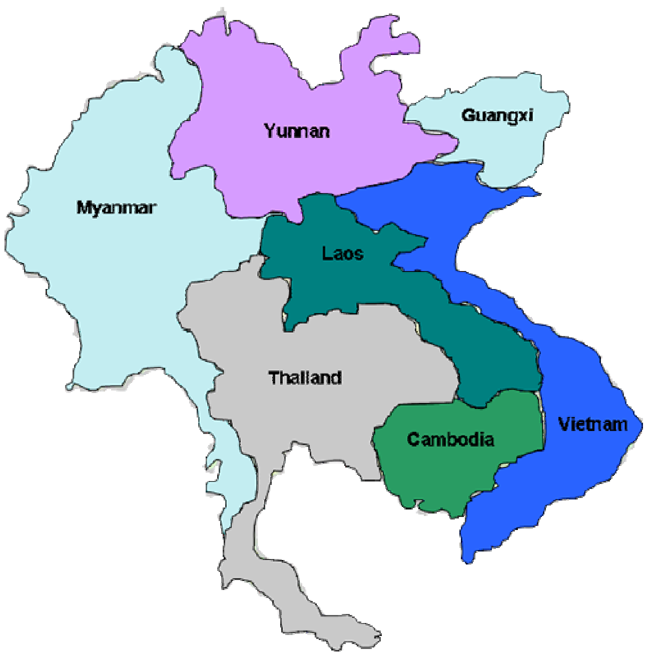

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CONTENTS

Load Shedding Control Strategy in an Electric Distribution System

Cattareeya Suwanasri, Thanapong Suwanasri, and Nuttapong Prachuab

Abstract— *This paper proposed the load shedding control planning in a distribution network in order to ensure power system stability and availability during system disturbances. The load shedding criteria are based on demand capacity for loss of power situation and load importance for loss of frequency. Two configuration of distribution networks as tap-tie normally open and radial with emergency line are presented as examples. The results show that this load shedding criteria are effectively manage demands during power system instability occurs. This planning strategy helps to reduce time in actual operating conditions as well as the costs of power system interruption.*

Keywords— **Load shedding, load importance, distribution system, loss of power, loss of frequency, demand management.**

1. INTRODUCTION

In the power system, if there is an excessive load over available generation, the generators will begin slowing down as they attempt to carry the excess load. The system frequency will be getting lower than a nominal frequency [1]. The drop in frequency may endanger the generator itself. As system frequency decreases, the power output begins to fall off rapidly. Thus the situation has a cascading effect with a loss of frequency leading to a loss of power [2]. To prevent the collapse of the system, load shedding schemes should be performed in order to balance the load to the available generation and recover from the under frequency condition [3]. To increase the service quality to their customers, electric utilities established certain planning and operating rules, so that the power system is able to face at each instant the current uncertainties (N-1 criteria). These rules do not cover all contingencies and do not offer the guarantee that the power system is completely protected against major incidents. However, these incidents that take place in distribution, transmission or interconnection networks have important economic impacts within the regions or countries where they occur. A generalized blackout, at country scale, completely collapses it during the necessary time needed to restore the normal functioning of the power system, which can take up to several days [4].

In Thailand, there are three major electric utilities; Electricity Generating Authority of Thailand (EGAT) who has a function to control generation and transmission system; the Metropolitan Electricity Authority (MEA) who is taking care of the distribution system in Bangkok, Nonthaburi and Samutprakan; and the Provincial Electricity Authority (PEA) who is taking care of the distribution system in the rest areas. However, they have collaborated to implement a manual to support the overloading condition in the system because the reliability has always been the prime concern of the electric utilities.

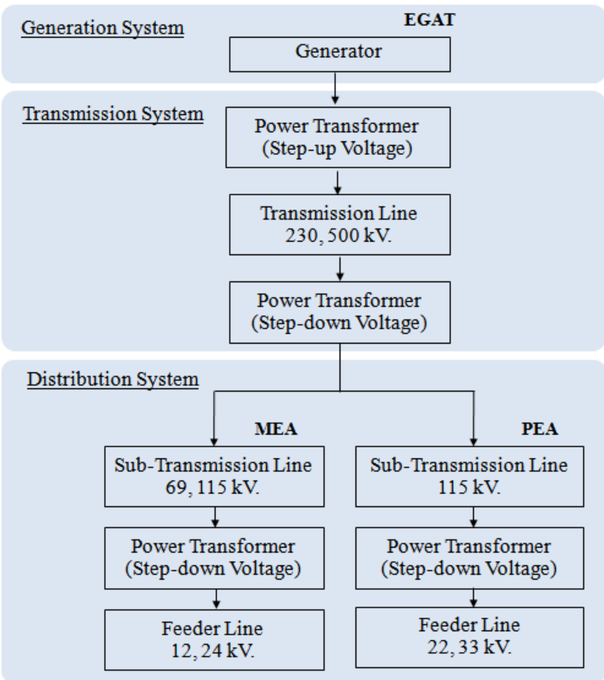

Fig.1. Transmission and Distribution Level in Thailand

In this paper, the load shedding control in the electric distribution system is proposed on the situations of a loss of power and a loss of frequency.

2. LOAD SHEDDING IN DISTRIBUTION SYSTEM

2.1 Load Shedding Control

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Nowadays, load shedding represents the final solution used to avoid voltage collapse, loss of synchronization, or overloads cascade on a wide area of power network after some resources have been exhausted while major consumers are powered during curative actions for these situations. Different techniques have been proposed to solve the load shedding problem in distribution network.

In [5], line ampacity violations and voltage drop violations at the load points are considering for load shedding in radial distribution systems. Ref. [6] explained load shedding in system with switch able capacitors and on-load tap changers. For voltage drop violations, the load point with violation, which does not have a switch able capacitor, will be shed. For current capacity violation at a component, a low priority load at a point beyond that component is shed. In [7], the effect of load-shedding on based on capacity and interrupting costs was investigated process when system instability occurs. In [8], an optimal load shedding strategy for power system with multiple DGs was presented. In [9-10], a genetic algorithm is employed to search for supply restoration and optimal load shedding in distribution networks.

In this paper, the load shedding control strategy based on load importance aspect as well as load capacity in the electric distribution system is proposed on the situations of a loss of frequency and a loss of power. Two configuration of distribution lines (tap-tie normally open, radial with emergency line) are presented as examples.

2.2.1 Load shedding on loss of power situation

The applications of overload shedding function are used to protect the cascading failure of power transformer(s). The consideration is involved with the maximum demand and the available capacity in each terminal substation. The available capacity can maintain the excess load up to 150% of rated for an hour. It is divided into two steps. In each step, loads are concerned about the outage area depends on demand capacity. The consideration of overload shedding scheme in both steps is the same, it is described as follows.

First priority considers a sub-transmission line that all connected load can be supplied by other neighboring sub-transmission lines. However, the capacity of neighboring line and power transformer(s) do not reach an overload situation as well.

Second priority considers a sub-transmission line that have the least load points still connected after almost load points were transferred to other neighboring sub-transmission lines in order to minimize the outage area.

2.2.2 Load shedding on loss of frequency situation

The applications of under-frequency relay are used to protect the generators. The functions of protective relay will depend on the strategy of each utility to control the system frequency. However, in this paper the procedure of load shedding on under-frequency relay is divided into five steps for 50 Hertz system frequency. In each step, load types are categorized by load importance. Load shedding from step 1 to step 5, the demands will be shed up to 50% of the total demand. Thereafter OFF 1 and OFF 2, the remaining demands will be shed each of 25% of the total demand until cover 100%. The load details are described as follows.

Step 1, 10% ± 1% of total demand is shed. The load type is mostly suburb residential areas.

Step 2, 10% ± 1% of total demand is shed. The load types are residential areas and some commercial areas.

Step 3, 10% ± 1% of total demand is shed. The load types are commercial areas and some small industrial areas.

Step 4, 10% ± 1% of total demand is shed. The load types are small industrial areas and some medium industrial areas.

Step 5, 10% ± 1% of total demand is shed. The load types are densely commercial areas, headquarter of commercial bank and medium industrial areas.

OFF 1, 25% of total demand is shed. The load types are industrial estates or large industrial areas, small hospitals and very important person household.

OFF 2, 25% of total demand is shed. The load types are Government areas, Palace area, medium and large hospitals, water pump stations and the internal electric system of substations.

Step OFF 1 and OFF 2 are the last shedding step. This highest priority feeders or loads will be disconnected only when the system nearly collapsed.

2.2 Distribution Systems

In a sample distribution system, the system is divided into two voltage levels as from the terminal substation to 115/69 kV sub-transmission line section and substation to 24/12 kV feeder line section.

Firstly, from the terminal substation to 115/69 kV sub-transmission line section, this refers to case of a power transformer failed, the demand will exceed remaining capacity. The sub-transmission line will be automatically shed via overload shedding function. There are two steps of overloading shedding function. Either step 1 and step 2 will automatically shed a specific line in four and two seconds, respectively; when the remaining demand still higher than the available capacity in order to protect the cascading effect on another power transformer(s).

Secondly, consider from substation to 24/12 kV feeder line, there is an application of underfrequency relay to protect the damage of generator due to prolonged operation at reduced frequency.

3. CASE STUDY AND ANALYSIS

3.1. Loss of Power Situation

For loss of power situation, the sample system, shown in Fig. 2, is at 115/69 kV level. The system consists of 8 terminal substations, 26 sub-transmission lines and 44 load points.

In Table I, the system data is described. For instance, two power transformers as rated of 100 MVA are connected at BUS-A while four power transformers as rated of 100 MVA are connected at BUS-D.

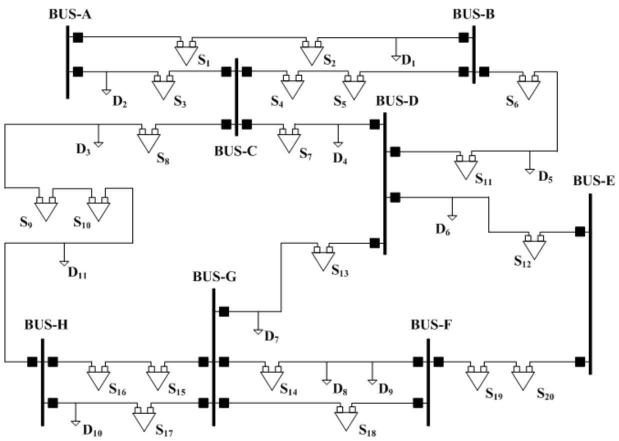

Fig.2. The 115/69 kV Power System Model

In Table II, the data of total 26 lines are given. For instance, line A1 is a connection between BUS-A to substation (S1) that demand of S1 as 70 MVA is connected. Similarly at line B1, the demands of S1, S2 and D1 as 45, 35 and 5 MVA are connected respectively.

Table 1. Total Capacity of Each Terminal Substation

Bus Name	Power Transformer (MVA)	Quantity	Total Capacity (MVA)
BUS-A	100	2	200
BUS-B	100	2	200
BUS-C	150	2	300
BUS-D	100	4	400
BUS-E	150	2	300
BUS-F	100	2	200
BUS-G	100	4	400
BUS-H	100	2	200

The criteria for loss of power situation are separated into two cases. Firstly, in case of the load on curtailed sub-transmission line cannot be transferred to a neighboring line; therefore, there is an outage on that disconnected line. Secondly, in case of the curtailed load can be transferred to a neighboring sub-transmission line; thus, the outage will not be occurred. The shedding situations are explained as following examples. At BUS-A, available capacity is 200 MVA as given in Table II, when there is a 100 MVA power transformer failed, the remaining capacity at BUS-A is 100 MVA while in that time the maximum demand is 160 MVA. By applying the regulation on 150% of the remaining capacity must be operated for an hour, thus the remaining power transformer supplies 150 MVA. This results to the minimum demand should be shed is 160 MVA-150 MVA = 10 MVA. However, this demand cannot be supplied by the neighboring terminal substations because they are operated at full capacity. Finally, this 70 MVA load connected at Line A1 must be totally shed. STEP 2 will be operated, if the remaining demand still excesses the capacity. At BUS-C, available capacity is 300 MVA, when a 150 MVA power transformer failed; the remaining capacity at BUS-C is 150 MVA while the maximum load is 255 MVA. The 150% of the remaining capacity must be operated, thus the remaining power transformer supplies 225 MVA. Therefore, the minimum demand should be shed is 30 MVA. In STEP 1, the 25 MVA load can be transferred and supplied by the neighboring terminal substation (BUS-D). However, the minimum demand as 30 MVA still excesses the curtailed demand as 25 MVA in STEP 1; therefore, STEP 2 operated. The 55 MVA in STEP 2 will outage because neighboring terminal substation operated at full capacity. This will be similarly to other cases in different buses to balance demand and supply during power outage situation. The shedding results are given in Table 3.

Table 2. Sub-transmission Line and Demand Data

Line	Detail	Load (MVA)	Line	Detail	Load (MVA)
A1	BUS-A to S1	S1 (70)	E1	BUS-E to S12	S12 (70)
A2	BUS-A to S3	S3 (65) D2 (25)	E2	BUS-E to S19	S19 (45) S20 (95)
B1	BUS-B to S1	S1 (45) S2 (35) D1 (5)	F1	BUS-F to S14	S14 (55) D8 (5) D9 (10)
B2	BUS-B to S5	S5 (35)	F2	BUS-F to S19	S19 (40)
B3	BUS-B to S6	S6 (40)	F3	BUS-F to S18	S18 (50)
C1	BUS-C to S3	S3 (55)	G1	BUS-G to S13	S13 (45) D7 (15)
C2	BUS-C to S5	S4 (40) S5 (30)	G2	BUS-G to S14	S14 (50)
C3	BUS-C to S10	S8 (20) S9 (35) S10 (40) D3 (10)	G3	BUS-G to S16	S15 (90) S16 (30)
C4	BUS-C to S7	S7 (25)	G4	BUS-G to S17	S17 (55)
D1	BUS-D to S7	S7 (35) D4 (10)	G5	BUS-G to S18	S18 (35)
D2	BUS-D to S6	S6 (45) S11 (70) D5 (15)	H1	BUS-H to S10	S10 (35) D11 (15)
D3	BUS-D to S12	S12 (65) D6 (30)	H2	BUS-H to S16	S16 (35)
D4	BUS-D to S13	S13 (50)	H3	BUS-H to S17	S17 (45) D10 (30)

3.2. Loss of Frequency Situation

For loss of frequency situation, the sample distribution system is at 24/12 kV as presented in Fig. 3. The system consists of 4 substations, 24 feeder lines and 35 load points which are divided into several types of areas such as residential area, commercial area and industrial area. Load details of each substation are given in Table IV.

For example, in Table IV at P-Substation, 6 feeders (P11 to P23) are connected. The major loads 15 MVA are connected to feeder P23, which is an internal electric system of P-Substation and palace area. The lowest priority load is defined as “1” and the highest priority load is defined as “7”.

When the demand highly exceeds the generation in power system, the loss of frequency situation occurs. The load shedding criteria are needed to be assigned in order to recover the system frequency. The priority load shedding based on load importance as described in section 2.2.2 must be performed. The feeder lines connected at P-Substation are then ranked against each other, the lowest priority feeders being targeted for load shedding first, the highest priority feeders are the last to be shed and typically first to have supply restored. The results are shown in Table V.

Table 3. Load Shedding Decision Caused by One Power Transformer Failed (* refers to outage occurs)

Remaining Capacity (MVA)	Maximum Bus Load (MVA)	150% of Remaining Capacity (MVA)	Minimum Load Curtailment (MVA)	Line Curtailment	Total Load Curtailment (MVA)
@ BUS-A 100	160	150	10	STEP 1 Line A1	70*
				STEP 2 Line A2	90
@ BUS-B 100	160	150	10	STEP 1 Line B2	35
				STEP 2 Line B3	40
@ BUS-C 150	255	225	30	STEP 1 Line C4	25
				STEP 2 Line C1	55*
@ BUS-D 300	320	450	-	STEP 1 Line D4	50
				STEP 2 Line D1	45
@ BUS-E 150	210	225	-	STEP 1 Line E1	70
				STEP 2 Line E2	140
@ BUS-F 100	160	150	10	STEP 1 Line F3	50
				STEP 2 Line F2	40
@ BUS-G 300	320	450	-	STEP 1 Line G1	60
				STEP 2 Line G5	35
@ BUS-H 100	160	150	10	STEP 1 Line H2	35
				STEP 2 Line H1	50

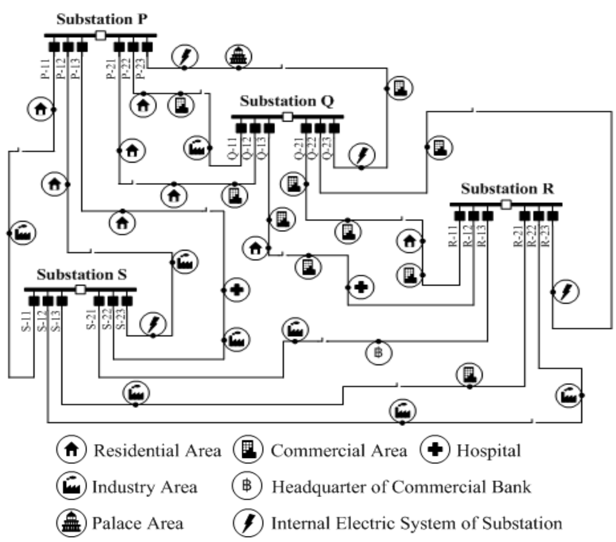

Fig.3. The 24/12 kV power system model

Table 4. Feeder Line and Demand Data

Sub.	Feeder	Description	MVA	Priority
P	P11	Residential Area	4	2
	P12	Suburb Residential Area	5	3
	P13	Residential Area	8	1
	P21	Suburb Residential Area	4	1
	P22	Commercial Area, Residential Area	6	2
	P23	Internal Electric System of P-Substation, Palace Area	15	7
Q	Q11	Small Industrial area	5	4
	Q12	Commercial Area, Residential Area	10	2
	Q13	Commercial Areas, Residential Area	9	3
	Q21	Commercial Areas	8	3
	Q22	Commercial Area	6	1
	Q23	Internal Electric System of Q-Substation, Commercial Area	12	7
R	R11	Densely Commercial Area, Residential Area	7	5
	R12	Small Hospital, Commercial Area	13	6
	R13	Headquarter of Commercial Bank	6	5
	R21	Densely Commercial Area	3	5
	R22	Medium Industrial Area	8	4
	R23	Internal Electric System of R-Substation	9	7
S	S11	Industrial Estate	11	6
	S12	Industrial Estate	15	6
	S13	Medium Industrial Area	4	5
	S21	Large Industrial Area	8	4
	S22	Small Hospital, Medium Industrial Area	10	6
	S23	Internal Electric System of S-Substation, Medium Industrial Area	14	7

Table V: Decision for Under-frequency Situation

Sub.	Step UF Relay					OFF1	OFF2
	1 49.0 Hz	2 48.8 Hz	3 48.6 Hz	4 48.3 Hz	5 47.9 Hz		
P	P13,P21	P11,P22	P12	-	-	-	P23
Q	Q22	Q12	Q13,Q21	Q11	-	-	Q23
R	-	-	-	R22	R11,R13, R21	R12	R23
S	-	-	-	S21	S13	S11,S12, S22	S23

In this case, the total demand in the system is 200 MVA. In STEP 1, when the system frequency decreases to 49.0 Hz, the 9-11% of total demand (18-22 MVA) must be shed, thus the residential loads (P13 and P21 feeder line) as the lowest priority are disconnected. If the system frequency still reduces to 48.8 Hz, STEP 2 must be operated. The next 9-11% of total demand must be shed, thus the second lowest priority in residential and commercial loads (P11 and P22 feeder line) are disconnected. If the system frequency cannot be recovered, the next steps will be subsequently operated. The highest priority loads as internal electric system of substation is the last step (OFF 2) to be shed.

4. CONCLUSION

The load shedding control strategy based on demand capacity and load importance in a distribution system is proposed in this paper. The tap-tie normally open configuration is presented for loss of power disturbance. The demand capacity aspect is applied to manage load shedding in this situation. The sub-transmission line that all connected load can be supplied by other neighboring terminal substations is firstly curtailed. Otherwise, the sub-transmission line, that the least load point(s) is connected, will be curtailed in order to minimize the outage area. Similarly, the radial with emergency line configuration is presented for loss of frequency disturbance. The load importance aspect is applied for this situation. The highest priority feeder is the last to be shed and normally the first to be restored. This planning strategy can effectively reduce operating time and interrupting costs during disturbance.

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Partial Discharge Detection in High Voltage Equipment Using High Frequency Current Transducer

Cattareeya Suwanasri, Pongsakorn Thawonsukanan, Sayan Ruankon, and Thanapong Suwanasri

Abstract— *This paper presents a development of the high frequency current transducer (HFCT) for off-line partial discharge detection. The NiZn ferrite core and the 37 turns of 24 SWG copper winding were used for the designed HFCT. Different objects such as basic objects and insulator were tested for internal discharge, surface discharge, air corona at the high voltage side, and air corona at the earth side in order to investigate the performance of the developed HFCT. The commercial tool according to IEC60270 partial discharge detection was used to detect the partial discharge signals as reference and compare with the signals from the developed HFCT. The results show that this HFCT can effectively detect the partial discharges in the frequency range between 100 kHz to 14 MHz.*

Keywords— **About four key words or phrases in alphabetical order, separated by commas.**

1. INTRODUCTION

Reliability and stability of electric power system are of prime concern. The high voltage equipment such as power transformer, generator, and surge arrester should be correctly operated. The performance of high voltage equipment steadily decreases with the age, usage, maintainance and operating environment. Especially at the insulation either solid as cross link polyethylene (XLPE), liquid as oil, or gas as air or SF_6, the insulation condition needs to be assessed and maintained to aviod any failures. Thus, the inspection and maintenance for the high voltage equipment must be properly performed in order to early detect the problems. Partial discharge (PD) is a major problem occuring in such high voltage equipment. It is localized electrical discharge resulting from ionization in a poor insulation system when the system voltage exceeds the inception voltage of impurity or air void inside the insulation. Partial discharge consists of internal discharge, surface discharge, and air corona. The presence of partial discharge in equipment leads to gradual deterioration of the electrical insulation. Consequently, internal faults or the total destruction of the equipment can be occurred. This results in insulation breakdown and subsequently the failure of the equipment. Therefore, it is necessary to detect the partial discharge, analyze discaharge pattern and violence of the partial discharge. As a result, the equipment in electrical network can be protected in time. However, it is diffucult to detect the partial discharge of insulation in the equipment because it always happens inside the equipment. Thus, the tools for partial discharge detection is required. In this paper, the partial discharge detector so called High Frequency Current Transducer (HFCT) is proposed to detect the internal and surface partial discharge as well as air corona. The test objects are developed for each test condition.

2. BASIC THEORY

2.1 Type of partial discharge

Partial discharge consists of internal discharge, surface discharge, and air corona [1]. Internal discharges occur at dielectric with a number of cavities of various sizes inserted between two carbon or matal electrodes as presented in Fig. 1. The discharge occurs when the supply voltage is higher than the inception voltage of cavities. Surface discharge takes place externally along the insulation surface between two metal or carbon eletrodes as shown in Fig. 2. External corona discharge occurring at a sharp metal point or edge is shown in Fig. 3. If the discharges occur on the negative half cycle of the sinusoidal test waveform, the location of sharp edge is at high voltage side. On the other hand, if the discharges occur on the positive half cycle of the sinusoidal test waveform, the location of sharp edge is at the earth potential.

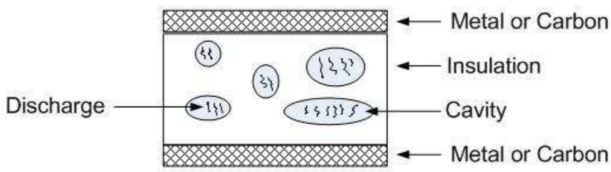

Fig.1. Internal Partial Discharge

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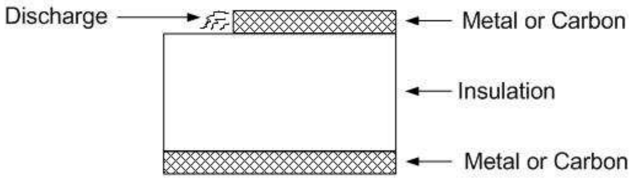


Fig.2. Surface Discharge

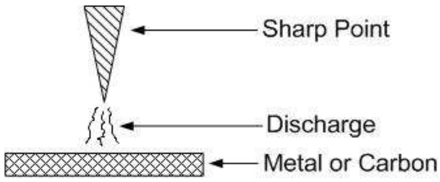


Fig.3. External Corona Discharge

2.2 Partial discharge detection

Partial discharge detection can be classified into two types that are on-line monitoring and off-line monitoring. The on-line testing techniques are such as ultrasonic PD detection, acoustic sensor and HFCT while the off-line testing techniques are as high potential testing, IEC60270 conventional PD detector, power factor/dissipation factor testing, very low frequency testing (VLF) [2]. Those PD detecting tools help to detect the abnormal condition at the beginnings of either small partial discharge, mechanic problems, arcing, surface contact of OLTC (On Load Tap Changer), or a loosen part inside transformer. Moreover, these tools can identify the problem's causes and severity. Then the maintenance can be properly acted. Partial discharge detection tecnique according to IEC 60270 standard [3], known as conventional method, is widely accepted with the highest accuracy. This technique can describe the phenomena of internal discharge, surface discharge, and air corona. The testing circuit is represented in Fig. 4. The circuit comprises coupling capacitor (C_k), filter (Z), input impedance of measuring system (Z_{mi}), connecting cable, coupling device, measuring instrument and test object (C_a).

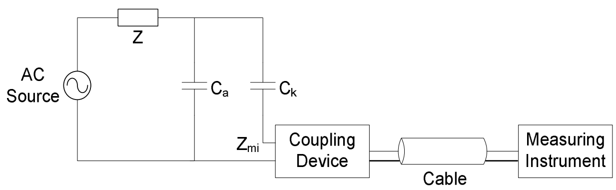
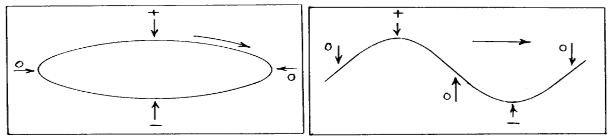


Fig.4. Basic IEC 60270 Discharge Detection Circuit

The discharge patterns are shown in the compendium as formalized diagram [1], in which the responses from individual discharges are supperposed on an elliptical time base that represents the sinusoidal test voltage. The positions of the voltage peaks and zeros and the rotation of the time base are indicated in Fig. 5 (a) and (b).



(a) Elliptical time base (b) Sinewave time base

Fig.5. Display of Discharge Patterns

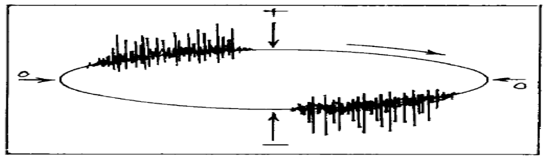


Fig.6. Internal Discharge Patterns

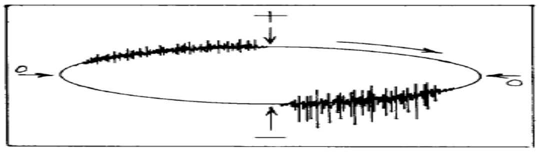


Fig.7. Surface Discharge Patterns

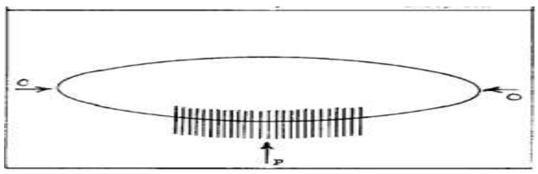


Fig.8. Corona Discharge Patterns

The discharge detection circuit in Fig. 4 can accurately detect incomplete discharge. The discharge results in form of elliptical time base of internal discharge, surface discharge, and air corona are given in Fig. 6-8.

For internal discharge in Fig. 6, the discharges occur approximately the same amplitudes on both half cycles. Number and location occur in advance of the voltage peaks. The number of discharges increases with the test voltage.

For surface discharge in Fig. 7, the discharges occur in advance of the test voltage peaks but the discharges on one half cycle of the test voltage waveform are greater in number but smaller in magnitude than on the other half cycle. There are degrees of random of variation in both amplitude and location. The number of discharges increases with the test voltage.

For corona discharge in Fig. 8, the discharges occur initially on one half cycle of the test waveform only. They are symmetrically disposed about the voltage peak. The equal magnitude and equally spaced in time can be observed from both cases. As the test voltage is raised the number of discharges increases rapidly and they spread out but are roughly symmetrical magnitudes about the peak.

However, the partial discharge detector in the market according the standard IEC 60270 is expensive. In this paper, then the High Frequency Current Transducer (HFCT) was developed. It is widely used in on-line partial discharge detection with discharge activity measurement in pC or nC.

3. DESIGN AND CONSTRUCTION OF HFCT

HFCT is one type of PD detector, which eliminates the low frequencies and passes the mid and high frequencies according to their frequency response characteristics [4-5]. The basic circuit of HFCT shown in Fig. 9 is used to detect partial discharge, as a fraction of its primary current (*i*) of HFCT, in form of output voltage across the resistor.

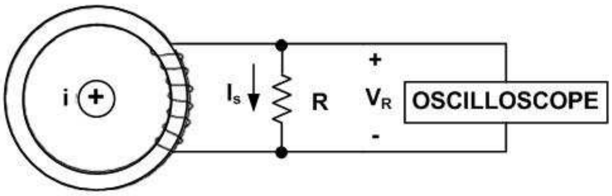


Fig.9. Basic Discharge Detection by HFCT

Where I_s is secondary current of HFCT, i is primary current of HFCT, R is resistive burden, V_R is output voltage of HFCT. The specification is given in Table 1.

Table 1. Specifications of HFCT

Parameter	Specification
Testing source	AC, 50 Hz
Core type, Core material	Toriod, NiZn
Winding	37 turns of 24 SWG Copper
Burden	Resistance 75Ω

Fig.10. Developed HFCT

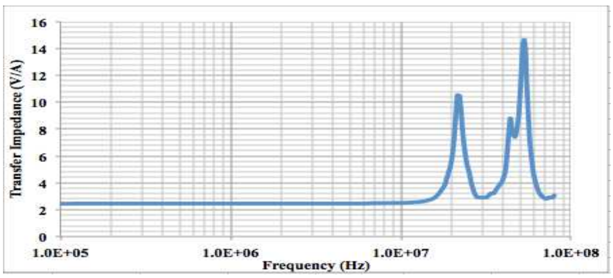


Fig.11. Transfer Impedance Versus Frequency

The designed HFCT is presented in Fig. 10. The response frequency is tested and presented in Fig. 11. This HFCT can effectively detect the PD in the frequency range between 100 kHz to 14 MHz.

4. EXPERIMENT SETUP AND RESULTS

4.1 PD testing circuit

The PD testing circuit is given in Fig. 12-13. It consists of AC power supply, conventional PD detector using the IEC 60270 standard (ICMsystem), PD detection using HFCT, voltage divider and test object. The results of PD detection by ICMsystem will be used as reference to verify the result from the HFCT. In Fig. 12, the test voltage is observed at CH1 by using voltage divider while the PD signal is observed at CH2 by using HFCT, which is connected at the system ground conductor.

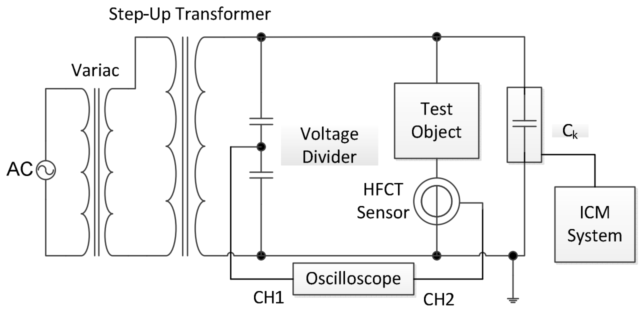


Fig.12. Experimental Setup

Fig.13. Internal Discharges Detected by ICMsystem

4.2 PD Testing Objects

Different objects shown in Fig. 14-17 are tested for internal discharge, surface discharge, air corona at the H.V. side, air corona at the earth side respectively in order to investigate the performance of the developed HFCT. The ICMsystem is used to detect the PD signals as reference and compare with the signals from the developed HFCT. The coupling capacitor (C_k) is connected to test object for signal proceeding to ICMsystem data acquisition and signal conditioning modules. Finally, a HV insulator is tested as a sample of HV equipment for internal discharge, surface discharge and air corona testing using HFCT.

4.3 Experimental Results

4.3.1 PD testing on basic objects

The voltage from 100 kV test transformer is raised until the PD occurs. The acquisition period is 30 seconds for any test. The test voltage is displayed in sinusoidal waveform. The discharge detected by ICMsystem is displayed in form of dots while by HFCT is displayed in form of voltage spites.

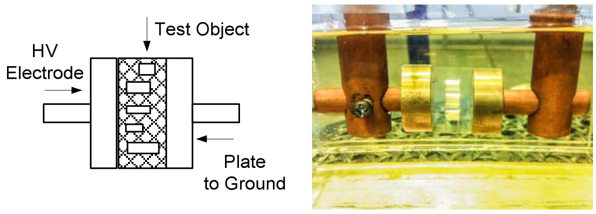


Fig.14. Internal Discharge in Oil

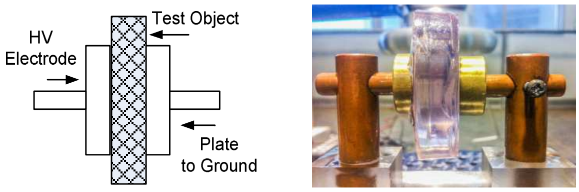


Fig.15. Surface Discharge

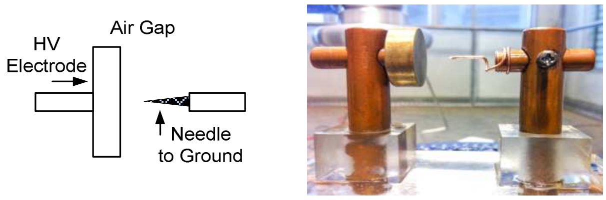


Fig.16. Air Corona; Needle to Ground

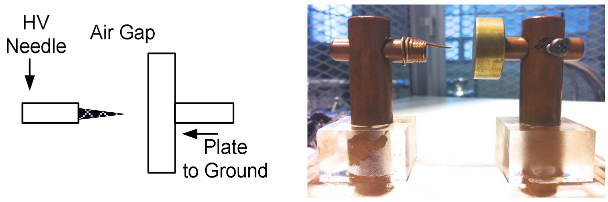
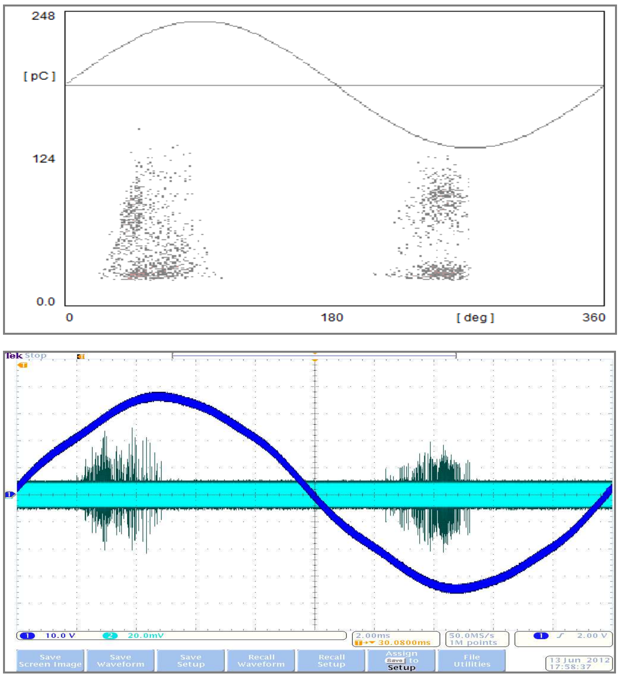


Fig.17. Air Corona; High Voltage Needle

For internal discharge in Fig. 18, the discharge occurred when the test voltage was up to 9.2 kV. The discharge amplitudes are nearly similar for both positive and negative cycles. The number and location of discharges from both ICMsystem and HFCT occurred in advance of the voltage peaks that are between 21-100 degree and 206-270 degree, respectively.

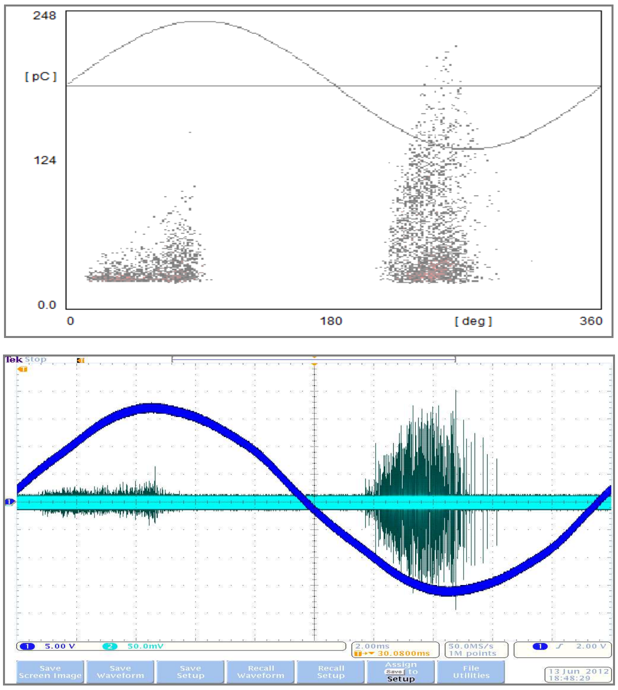
For surface discharge in Fig. 19, the discharge occurred when the test voltage reached 4.3 kV. The discharges occur in advance of the test voltage peaks that are mainly between 10-92 degree and 208-289 degree. But the discharge magnitudes on positive cycle are smaller than that on negative cycle. The negative discharge amplitude is about 2 and 4 times greater than the positive discharge amplitude for ICMsystem and HFCT respectively.

For corona discharges in Fig. 20, the discharges occurred only at half of cycle of the test waveform but they are symmetrical around the voltage peak. The corona discharge at the H.V. side happened when the test voltage was up to 2.3 kV, the discharges occurred between 250-274 degrees. For air corona discharge at the earth side in Fig. 21, the test voltage was up to 2.5 kV the discharges occurred between 60-110 degree.



(a) Detecting by ICMsystem (b) Detecting by HFCT

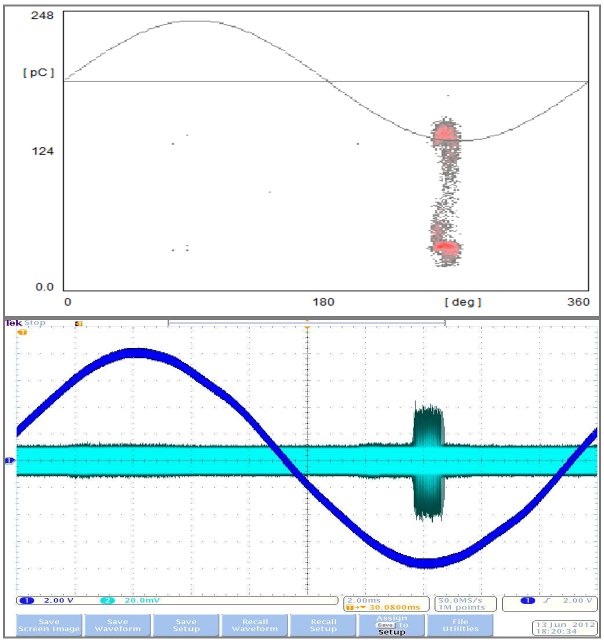
Fig.18. Internal Discharge Detection



(a) Detecting by ICMsystem (b) Detecting by HFCT

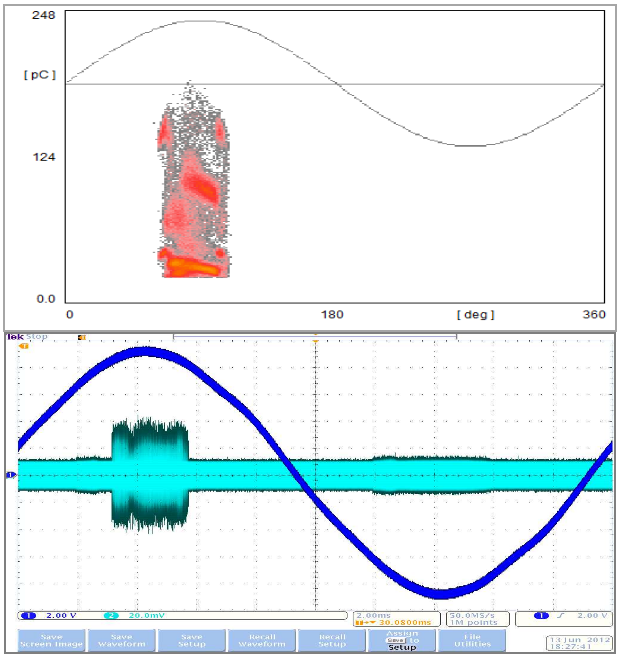
Fig.19. Surface Discharge Detection

The results show that the designed HFCT can successfully detect the internal discharge, surface discharge, air corona at H.V. side, and air corona at the earth side in the frequency range between 100 kHz to 14 MHz. The HFCT partial detecting results were confirmed by comparing with the results from a commercial tool according to IEC60270 standard for PD detection.



(a) Detecting by ICMsystem (b) Detecting by HFCT

Fig.20. Air Corona Detection; Needle to Ground



(a) Detecting by ICMsystem (b) Detecting by HFCT

Fig.21. Air corona Detection; High Voltage Needle

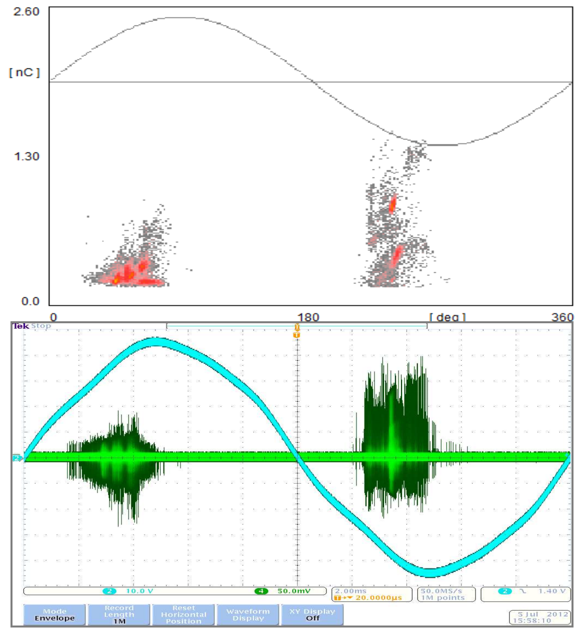
4.3.2 PD testing on HV insulator

The PD testing results show in Fig. 22-24. The designed HFCT can detect the surface discharge on normal insulator, internal discharge in punctured insulator, and air corona at the H.V. side on a humid condition.

In Fig. 22, the discharge on the normal insulator occurred when the test voltage reached 30.11 kV. The discharges occur in advance of the test voltage peaks that are mainly between 23-82 degree and 212-274 degree. But the discharge magnitudes on positive cycle are smaller than that on negative cycle.

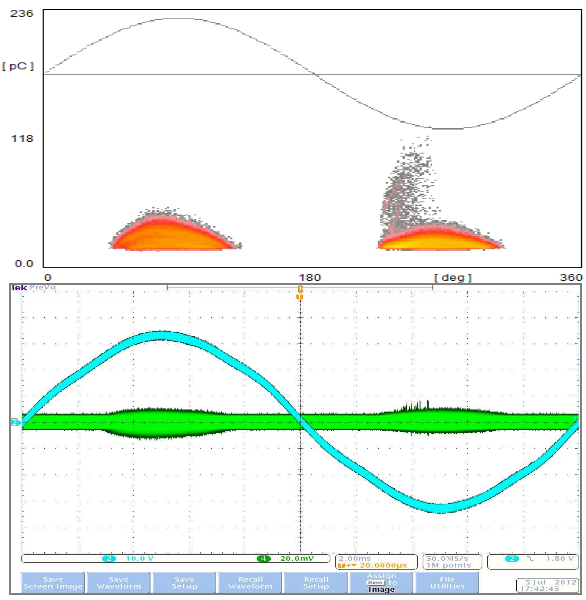
In Fig. 23, the discharge on the puncture insulator occurred when the test voltage was up to 22.11 kV. The most of discharge amplitudes are nearly similar for both positive and negative cycles. The number and location of discharges from both ICMsystem and HFCT occurred in advance of the voltage peaks that are between 21-100 degree and 223-308 degree, respectively.

In Fig. 24, the discharges on humid insulator occurred only at negative half of cycle of the test waveform. The corona discharge at the HV side happened when the test voltage was up to 30.25 kV, the discharges occurred between 251-272 degrees. These results from the HFCT detection were similarly compared and confirmed with the results from a commercial tool according to IEC60270 standard for PD detection.



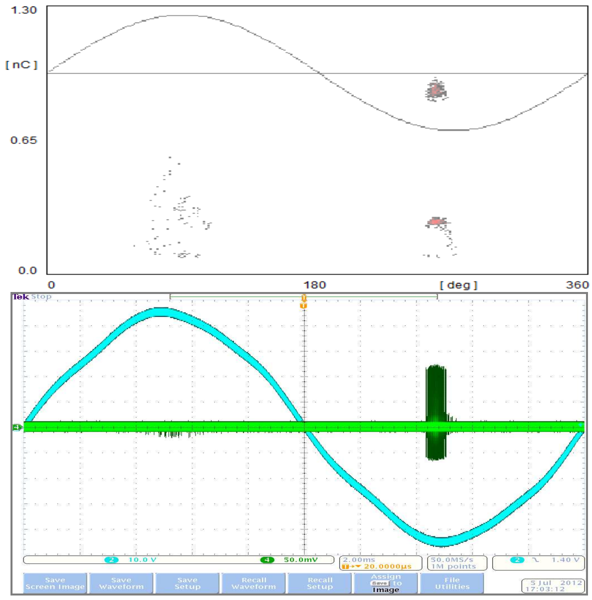
(a) Detecting by ICMsystem (b) Detecting by HFCT

Fig.22. Surface Discharge on Normal Insulator



(a) Detecting by ICMsystem (b) Detecting by HFCT

Fig.23. Internal Discharge in Punctured Insulator



(a) Detecting by ICMsystem (b) Detecting by HFCT

Fig.24. Air Corona at the H.V. Side on Humid Insulator

For all tests, the background noises from the environment were 8 pC and 11 mV, which were measured with IEC60270 and HFCT, respectively.

4.3.3 Practical implementation

HFCT is an effective tool for on-line partial discharge measurement due to it can be performed at site while the equipment is energized in service. Since the HFCT is used as clamp-on device around the ground wire connecting between equipment grounding terminal and system grounding, it can measure almost all types of high voltage equipment such as power transformer, power circuit breaker, instrument transformer etc. Moreover, due to its advantages of easy for installation, less time consuming and no service interruption, this method is now preferred for field measurement to quickly investigate the partial discharge at site. However, the measurement comparison with conventional PD measurement system, background noise reduction and filtering system should be further investigated to obtain the reliable result.

5. CONCLUSIONS

In this paper, the HFCT were developed for off-line partial discharge (PD) detection such as internal discharge, surface discharge, air corona at the H.V. side, and air corona at the earth side. The NiZn ferrite core and the 37 turns of 24 SWG copper winding were used in the design and construction. Four different object-types as well as the HV insulator were tested. The results show that the designed HFCT can successfully detect the internal discharge, surface discharge, air corona at the H.V. side, and air corona at the earth side in the frequency range between 100 kHz to 14 MHz. The HFCT partial detecting results were confirmed by comparing with the results from a commercial tool according to IEC60270 standard for PD detection. This HFCT can be further developed for on-line PD detection of the high voltage equipment such as power transformer.

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The Analysis of Renovation Criteria for Protective Relay in Power Substation

Thanapong Suwanasri, Cattareeya Suwanasri, Tospon Hearunyakij, and Sarawut Wattanawongpitak

Abstract— *This paper proposes the renovation criteria for protective relay in control and protection system within power substation. The important criteria consist of age, stress, symptom, obsolescence and failed type. The procedure for the renovation of protective relay is presented. Firstly, the basic information of the existing protective relays in the utility is analyzed. Secondly, the data analyzes are performed such as the classification of different technologies, number manufacturers, ages, future trends, and etc. In this stage, the total of 25,370 protection relays from 221 high voltage substations is analyzed. Finally, the performance evaluation for the sample protective relay is given as example.*

Keywords— **Protection relay, renovation, age, stress, symptom, obsolescence, failed type.**

1. INTRODUCTION

In high voltage substation, the primary equipment, such as power transformer, power circuit breaker, instrument transformer, and surge arrester, are the main components for energy transfers in the network. Whereas the secondary equipment; control and protection system and communication system, are used to support the primary equipment in order to incorporate all functions and maintain the acceptable reliability in power system as effectively as possible.

In control and protection system of high voltage substation, one of the most important devices is the protective relays. The main function of protective relays is to monitor the electrical activity and trip the circuit breakers whenever electrical fault is detected within the system. The technology of protective relay in high voltage substation has been improving over the past decades. Electromechanical relay has been operated in the late 19th century by using magnetic attraction [1]. Then, the protective relay has been developed into static relays in the early 20th century. Static relays have higher sensitivity than electromechanical relays because of a separate supply that generates power to operate the output contacts instead of signal circuits. Static relays offer low contact bounce, fast-long-life operation, and low maintenance. In the present depending on renovation strategy, most electromechanical relays have been replaced with microprocessor-based digital relays or sometimes called numerical relays. By using microprocessor, the digital relays have the ability to combine the functions of many electromechanical relays into one device. They also provide additional features; such as communications interface with SCADA, waveform analysis, and metering.

Because of fast pace in technology, some outdated equipment have to keep up with modern system. By just refurbishing from old to new equipment using the same technology may not be enough to fulfill the function of modern technology in protection system. Therefore, method of renovation is required to upgrade the relays in protection system in order to be compatible with other communication systems within high voltage substation. In this paper, the performance evaluating criteria for renovation of protective relay in a control and protection system are proposed. Then the decision of renovation can be achieved.

2. IMPORTANT ASPECTS FOR PROTECTION SYSTEM IMPROVEMENT

The following aspects are a guideline for proper renovation criteria of protection system improvement, which would cover the equipment that is either in used or in stock. These aspects should be carefully analyzed and compared in terms of both technical and economical aspects.

1. *Customer Impact*: any malfunction of the equipment that causes service interruption or supply outage to the customers. For example, equipment malfunction causing power outage can affect the industry's productivity, which results in the lost of revenue.
2. *Maintenance Expense*: when the lifetime of the equipment passes over its average lifetime, the equipment's condition and performance degrade rapidly. Therefore, it is uneconomical to renovate or refurbish because of the higher maintenance cost.
   2.1 *Preventive Maintenance* (PM) refers to the maintenance of the equipments periodically. The main purpose is to check the readiness of equipments' functional performance. Therefore, the time-based maintenance must rely on the equipments' malfunction statistic and the

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manufacturer recommendation for specify the period of maintenance.

2.2 *Corrective maintenance* (CM) occurs when the equipment is malfunctioning. This type of maintenance is separated into two categories.

- *Initial Maintenance*: This type of maintenance is usually done immediately at the site. The majority of this maintenance is often referred to slight damage only.
- *Critical Maintenance*: This type of maintenance could not be performed immediately at the site. It requires the replacement of the damaged equipment with the new equipment from the stock. The maintenance of the damaged equipment has to be performed elsewhere in the maintenance facility.

3. *Equipment Performance*: the increasing number of equipment malfunction can affect the supply service quality and increase the maintenance cost.
4. *Environmental Change and Support*: the variation in fault current and load growth from the increasing of power demand.
5. *Spare Part*: some manufacturers could have no longer produced the spare part for the particular equipment or could have upgraded to different model; therefore, the manufacturers would increase the price of the spare part.
6. *Safety*: the safety issue of equipment operation affects the safety of the employees as well as the nearby equipment in case of explosion.
7. *New Technology*: the employee could not keep up the maintenance process with the fast growing new technology. Thus the training is required.

3. CRITERIA FOR RENOVATION OF PROTECTIVE RELAY

The criteria for renovation of the secondary equipment in control and protection system as well as communication system can be classified into five categories such as age, stress, symptom, failed type, and obsolescence [3]. The details are described as follows.

Aging refers to the deterioration of the equipment's strength over the chronological time. Certain materials in the equipment deteriorate over time until some types of failures occur. The aging of the equipment can start from the beginning of usage or as it comes out of factory.

Electrical stress can cause parts to fail whilst in service both during test and/or the assembly is in the field. Some of these failures occur due to faults in manufacture, test or operation; others are the result of external events.

Symptom means any signs of power disturbance that could lead to electrical failure in the system. These symptoms can be inspected through visual or other electrical devices. Some parts of the equipment can also show the sign of failure symptom that leads to equipment failure as a whole.

Failed types are based on the statistic data of the equipment model that has problems or has failure in high voltage substation. In order to avoid the interruption within the system, certain failed type model would be removed or replaced by other more reliable model into the system.

Obsolescence involves spare parts unavailability, technology modernization, and after sale service, are sample criteria of problems in obsolescence of electrical power equipment.

The problem of protection system in traditional high voltage substation is that some of protective relays are out of date. Thus, the planning for renovation of protective relay generally refers to the age and failed-type criteria. However, other criteria such as electrical stress, electrical symptom, and obsolescence are unavoidable.

4. WEIGHTING AND SCORING OF SOLID-STATE RELAYS

The details of weighting and scoring for evaluation criteria of solid-state relays are shown below as example for protective relay in secondary system in HV substation.

4.1 Age Criterion

The aspects for age criterion are such as age, application, and warranty period. The weight and score of each aspect are given in Table 1 and Table 2, respectively.

Table1. Weighting for age criterion

Criteria	Weight %
Age	40
Application	30
Warranty period	30

Table 2. Scoring for age criterion

Criteria	Scoring for Aging Aspects				
	0	1	2	3	4
Aging	0-30	-	-	-	> 30
Application	Backup	-	-	-	Primary
Warranty period	Valid	-	-	-	Expired

4.2 Electrical Stress Criterion

The aspects for stress criterion are such as electrical system requirement, testing and maintenance after installation, installation model, temperature in cubicle, humidity in cubicle and thermostat in cubicle. The weight and score of each aspect are shown below in Table 3 and Table 4, respectively.

Table 3. Weighing for Electrical Stress Criterion

Criteria	Weight %
Electrical system requirement	20
Testing and maintenance after installation	5
Installation model	15
Temperature in cubicle	20
Humidity in cubicle	20
Thermostat in cubicle	20

Table 4. Scoring for Electrical Stress Criterion

Criteria	Scoring for Electrical Stress Aspects				
	0	1	2	3	4
Electrical system requirement	Operational	-	Emerging limitation	-	Maintenance required
Testing and maintenance after installation	1	-	2	-	> 2
Installation model	Indoor with air condition	Outdoor with air condition	Indoor without air condition	-	Outdoor without air condition
Temperature in cubicle	Low	-	Medium	-	High
Humidity in cubicle	Low	-	Medium	-	High
Thermostat in cubicle	Available	-	-	-	Unavailable

4.3 Electrical Symptom Criterion

For electrical symptom criterion, weighting factors are shown in Table 5 whereas scoring factors of those aspects are given in Table 6.

Table 5. Weighing for Electrical Symptom Criterion

Criteria	Weight %
Visual inspection	15
Functional operation	60
Power supply failure	25

Table 6. Scoring for Electrical Symptom Criterion

Criteria	Scoring for Electrical Symptom Aspects				
	0	1	2	3	4
Visual inspection	Normal	-	-	-	Damaged
Functional operation	Normal	-	-	-	Damaged
Power supply failure	Normal	-	-	-	Damaged

4.4 Failed-type Criterion

The failure rates must be calculated in terms of failure frequency. The scorings of failed-type aspect are classified into five levels depending on the failure rate which are defined in Table 8. Because of the failed-type criterion has only one aspect, the weighting factor of failure rate is equal to 100%.

Table 7. Weighing for Failed-type Criterion

Criteria	Weight %
Failed-type	100

Table 8. Scoring for Failed-type Criterion

Criteria	Scoring for Failed-type Aspects				
	0	1	2	3	4
Failed-type	Low	-	Moderate	-	High

4.5 Obsolescence Criterion

There are four aspects such as availability of spare parts, after sale service quality, technology obsolescence, and maintenance expense in obsolescence criterion. Each aspect is weighted and scored as presented in Table 9 and Table 10, respectively.

Table 9. Weighing for Obsolescence Criterion

Criteria	Weight %
Availability of spare parts	35
After sale service quality	15
Technology obsolescence	30
Maintenance expense	20

5. PERFORMANCE INDEX CALCULATION

The scoring and weighting techniques are in the form of multi-attribute or multi-criterion analysis. It involves identification of the non-monetary factors that are relevant to the project. The allocation of weights to each of them reflects their relative importance. The allocation of scores to each option reflects how it performs in relation to each attribute. The result is a single weighted scored for each option, which may be used to indicate and compare the overall performance of the options in non-monetary terms.

Table 10. Scoring for Obsolescence Criterion

Criteria	Scoring for Obsolescence Aspects				
	0	1	2	3	4
Availability of spare parts	Easy to find	Required time	Slowly producing	Insufficient, No longer produce, High price	No longer produce particular spare part
After sale service Quality	Good	-	Moderate	-	Bad
Technology obsolescence	Operational	-	Becoming obsolete	-	Obsolete
Maintenance expense	Low	-		-	High

The scoring technique is used for classifying the condition of HV circuit breaker into several levels such as healthy, moderate/need caution and risk. The weighting technique is used for ordering an importance of each criterion. Percent factors are obtained by utilized the scoring and weighting factor. The health index (HI) can be achieved by comparing with the percent factors and finally the evaluated condition is presented according to traffic light sign: green as healthy, yellow as moderate/need caution, and red as risk. The equations of health index and renovation index are shown in Eq. (1) and Eq. (2) respectively [2].

$$HI(\%)=\frac{\sum_{i=1}^{n}(s_i \times w_i)}{\sum_{i=1}^{n}(s_{i,\,max} \times w_i)}\times 100 \tag{1}$$

$$RI(\%)=\frac{\sum_{j=1}^{m}(\%HI_j \times W_j)}{\sum_{j=1}^{m}(S_{j,\,max} \times W_j)}\times 100 \tag{2}$$

$$PI\ (\%) = 100 - RI(\%) \tag{3}$$

High renovation index refers to the high requirement of equipment renovation. The performance index of equipment is calculated as given in Eq. (3). Similarly, the higher performance index is the better condition.

For overall renovation criterion, five aspects are considered as given in Table 11. Each aspect is weighted and subsequently used to calculate the overall performance.

Table 11. Weighing Results for Renovation Criteria

Renovation Criteria	Overall Weight (%)
Age	40
Electrical stress	5
Electrical symptom	5
Failed-type	40
Obsolescence	10
Total	100

Table 12 shows the determination criteria of performance index as color bands representing green as good or healthy condition, yellow as moderate or required maintenance planning, and red as poor or risky condition requiring reparation or renovation as soon as possible.

Table 12. Performance Index

Performance Index		
Healthy	> 75%	Green
Moderate	50% - 75%	Yellow
Risk	< 50%	Red

6. ECONOMIC ANALYSIS

After the techinical evaluation of protective relay is done, the decision of different renovation options will be further depending on the economic analysis. Three basic renovation strategies, which are big-bang, progressive change, and refurbishment, have been proposed [2]. The first is big-bang method that includes removing and rebuilding the entire system. This method is cheaper than the progressive change because there is no long term development of specific interoperation interface and requires only a single configuration and test effort. The second is progressive change method, which refers to the renovation of one bay or a set of bays without interfering with other bays. This method would improve continuously with rapid installation on each bay. It also facilitates into yearly budget. The third is refurbishment that involves retrofitting modern technology with the existing protection system. It allows a reduction of cost, but improves the system's performance. Some options of refurbishment include device replacement, rack replacement, extension of existing installation, and complete scheme replacement. The decided method will depend on the appropriate situation among cost reduction of the user.

7. CASE STUDIES OF PROTECTIVE RELAY

This section proposes the procedures for the renovation of protective relay in high voltage substation as an example. To renovate the protective relay, the basic information of the existing relays in the utility must be firstly analyzed. Secondly, the data analysis should be performed such as the classification of different technologies, number manufacturers, ages, future trends, and etc. Thirdly, the obsolescence criteria should also be taken into consideration. Finally, the economic analysis must be evaluated for selecting the best renovation method.

7.1 Basic Information

Protective relay in high voltage substation has its own aging duration. Protection ageing refers to the usage duration of the relay in the protection system. The maximum aging of relays depends on the type of technologies and the usage.

Electromechanical relay is a conventional type of protective relay [4]. It has the longest aging because of its magnetic mechanical that has no random failure rate. In many high voltage substations, this type of relay has been installed for over 35 years. However, this electromechanical technology has limitation of multi-function for operating with other modern equipment in the control and protection system. Therefore, this type of technology has been slowly obsolete and has been replaced by the modern technologies. Solid state relay was then introduced into the protection system in order to reduce the operation of the moving parts causing to failure from electromechanical relay. However, by the fast discovery of numerical technology of protective relay with the better multi-function, then the number of solid state relay has been reduced. Then most of solid state relay has been aged of 15 years. In the present, numerical relays are the modern technology that equip with many functions in a compact design. With their advantages, this technology has been increasingly used in any modern substation. Especially in smart grid and automation system, these relays provide more benefits for overall capability. In contrast, when different types of relay are simultaneously used in high voltage substation, their functions or parts of any equipment would have chance of incompletely functional or fully nonoperational, which could lead to failure within the system. Therefore, the best technology should be selected for installation. Then obsolete equipment must be evaluated in terms of technological and economical aspects. In order to evaluate the obsolescence criteria, extensive data gathering has to be done. Failure rate criteria and critical network risk are examples that require gathering the fault record over the long period of time. Cost, spare arts, and new performance requirements are the criteria that may require restricted financial data. However, protection age and technology obsolescence criteria can be easier to evaluate by just using the model number, the type of technology, and the startup date in the database.

The methodology to determine the protection aging and technology obsolescence of protection relays in high voltage substation is as shown in Fig. 1.

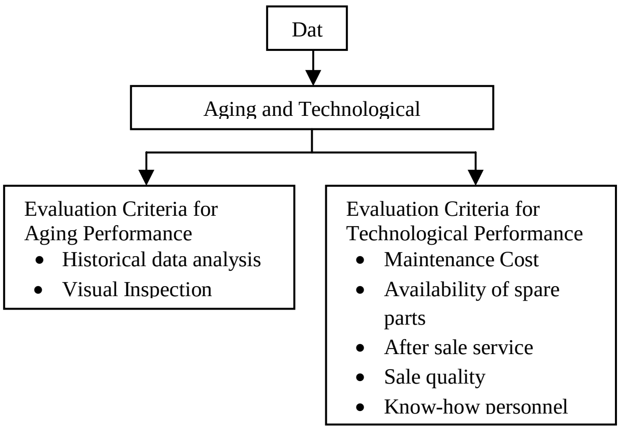

Fig.1. Protection Relay Renovation Method

Firstly, the gathering equipment data from major high voltage substation database is classified and prepared data such as the type of relay, installation date, location, manufacturers for further analyses. Secondly, the technical data from several criteria as aging and obsolescence of protection relays in database is analyzed. Thirdly, aging performance is evaluated based on historical data and visual inspection such as condition and function operation in good, moderate or bad condition. Next, evaluate technology obsolescence based on historical data, availability of spare parts, after sale service, sale quality, know-how personnel, and manufacturers. Then, the economic aspect of maintenance strategies, such as refurbishment or renovation with the present or modern technology as well as replacement the equipment or whole system because of technology obsolescence, are analyzed. Lastly, the best renovation option can be decided.

7.2 Data Analysis of Existing Protective Relay

The total of 25,370 relays in 221 power substations at 115 kV, 230 kV, and 500 kV level are given as examples on the age and technology obsolescence criteria for the renovation of the protective relay. The total number of different technologies of protective relays in the electric utility in Thailand is shown in Fig. 2. It shows that the modern technologies as solid state relay and numerical relay are replacing the old technology as electromechanical relay.

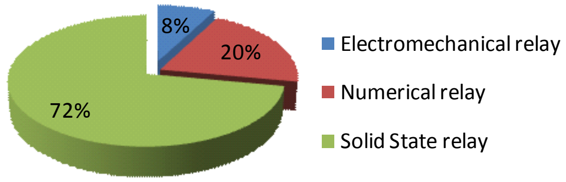

Fig.2. Types of Protective Relay from 115 kV up to 500 kV

7.2.1 Technology Usage

Fig. 3 shows the numbers of different relay technologies in different manufaturers. The utility mostly uses static relay because they are funtional and compatible to the present control and protective devices as shown in manufacturers A and B. Whereas, the manufacurer C mostly supply the highest number of numerical relay comparing with other technologies. In addition, this numerical relay keeps steadily incresing into to the modern system. However, the number of electromechanical is significantly low comparing to the others. This is because of its obsolete technology and limitation of functionalty.

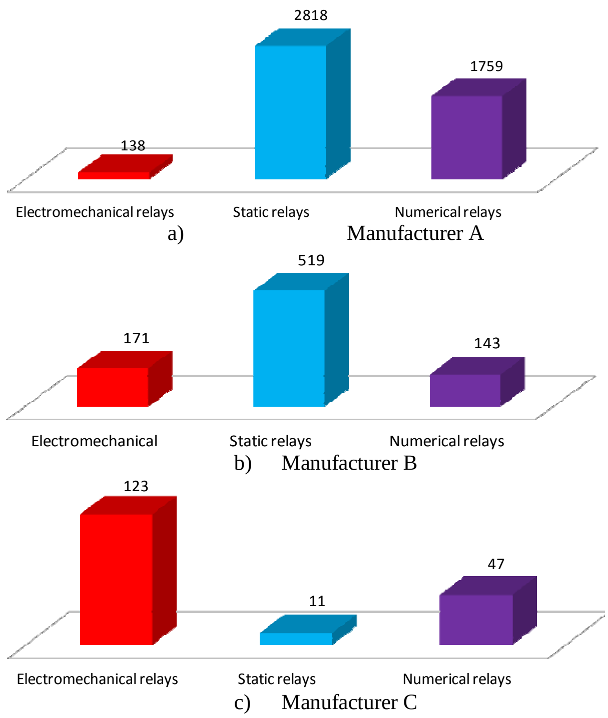

Fig.3. Number of Relays in Different Technologies

7.2.2 Aging Evaluation

Aging is one of the performance criteria that can easily be used as evaluation for renovation decision. That can refers to the deterioration of the equipment's strength over the chronological time. In general, the end of life for protective relay depends on their technologies; normally 20 years for electromechanical relay, 15 years for solid state relay, and 10 years for numerical relay.

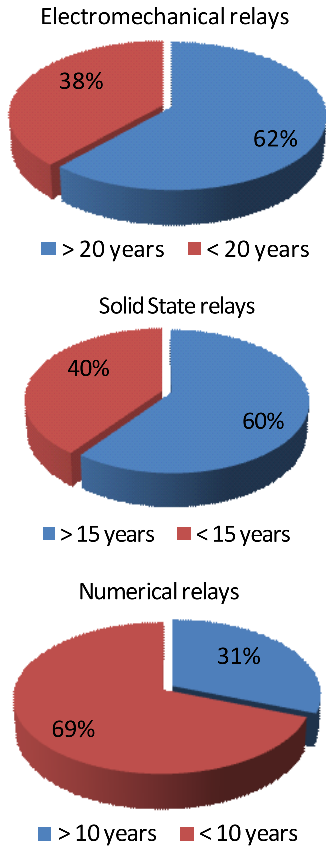

Fig.4. Aging Percentage of the Protective Relay

Fig. 4 shows the percentage of the age of protective relay separated by types as electromechanical relay, solid state relay and numerical relay. Majority of age as 62 % for electromechanical relay are more than 20 years whereas 60 % of solid state relay are more than 15 years. However; numerical relay is the latest technology in the system, then only 31% are used more than 10 years.

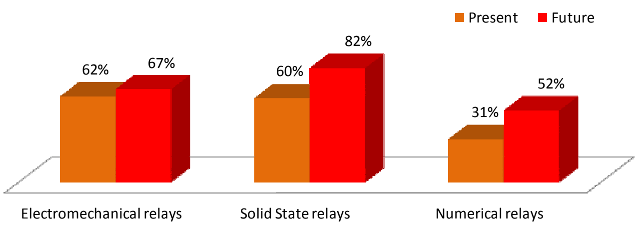

Fig.5. Aging Trend of Protective Relay in the Next Decade

The future aging trend of protective relay in the next decade is shown in Fig. 5. It shows that the number of electromechanical relay aging (>20 years) keeps slightly increasing from 62% to 67%. Whereas the usage of solid state relay (>15 years) and numerical relay (>10 years) are significantly increasing for 60% to 82% and 31% to 52%, respectively. This means the electromechanical relay is nearly obsoleted due to its disadvantage on operational function while numerical relay is dispersing in the modern protection system due to its advantage on mutiple operational function.

7.2.3 Performance Index Calculation

In Table 13, using Eq. (1) health indices of all renovation criteria are given. Using Eq. (2), the renovation index is equal to 30% that means the performance index is equal to 70% by using Eq. (3). Therefore, overall performance of the sample protective relay in HV substation is concluded. The overall performance is in the moderate zone that implies to require maintenance planning for such relay.

Table 13. Performance of a Sample Protective Relay

Criteria	HI (%)	Overall Weight (%)	RI (%)	PI (%)
Age	40	40	30%	70% = Moderate condition
Electrical stress	20	5		
Electrical symptom	40	5		
Failed-type	20	40		
Obsolescence	30	10		
Total		100%		

8. CONCLUSION

The criteria for renovation of protective relay in HV substation include age, stress, symptom, obsolescence and failed type. The most influent criteria affecting to the renovation decision are age and failed-type, which both criteria have the weights as of 40 percent. From the statistical record of a Thai utility, it is clearly that electromechanical relay is now considered to be obsolete comparing to static and numerical relay. Therefore, the renovation process should be performed either refurbishment or renovation. The renovation criteria, method implementation and performance evaluation of solid-state relay are given as example. To fullfill the optimum decision, both of technical and economical aspects must be analyzed. The proper option with the highest cost reduction is choosen. Finally, the appropriate renovation of protective relay in high voltage substation can be accomplished.

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Sustainable Management of Small Hydropower for Rural Electrification in Lao PDR by Economic Blueprint Perspective

Akhomdeth Vongsay and Xayphone Bounsou

Abstract— *Electric energy generation mostly from hydroelectric power, thermal power, nuclear power and renewable sources is one of the major key factors for economic and social development in the entire developed and developing nation of the world. The Government of Laos (GoL) has declared that the small hydropower (SHP) with the capacity less than 15 MW is Renewable Energy (RE).The main challenges for the Government of Laos is how to manage the SHP for the sustainable ways in order to contribute for the GoL's golden target for household to have electricity for 90% in the year 2020. Currently, the government has already approved 35 projects with the capacity less than 5 Mw for the rural development. In this study the main purpose is to analyze the 12 existing small hydropower projects in Lao PDR (with the capacity less than 5 MW) that was not sustainable then will propose the recommendation the suitable management tools by using the Economic, Social and Ecological blueprint model (ESE model). In this paper will introduce only the concept of the economyblueprint perspectivethat is one of the three perspectives in the ESE model.*

Keywords— **Sustainable, small hydro project (SHP), government of Lao PDR (GoL), economic, social and ecological blueprint model (ESE model).**

1. INTRODUCTION

Electric power system of Lao PDR is separated into three parts by regions (Northern, Central regions and Southern) because there is no national grid connected from north to south the extensions of electric power grids to remote households are either prohibitively expensive or economically unjustified.

A recent World Bank study estimates that more than 1.8 billion rural people or two thirds of total rural population in developing countries still have not attained any grid-based electricity services [1].

In many Asian and African countries such as Bangladesh, Botswana, Ethiopia, Kenya and Yemen, less than 5 percent of rural villagers have access to grid services [2].

Rural electrification is often the preferred program for promoting equity and development in poor countries. Several reasons account for this. First, electricity is perceived as a modern source of energy, essential to development. In most parts of the world, areas without electricity are far less developed than those with access.

The Government plans to expand electrification in remote areas through two methods. One is to expand the grid to comparatively easily accessible areas. The other is to provide off-grid supplies to remote areas where it is difficult to expand the present grid due to environment or cost reasons [3].

In rural areas, electricity serves many purposes. It can improve business and farm productivity, ease the burden of household tasks, and provide more efficient lighting for rural families. Increased accessibility to electricity in rural areas will improve living standards and help reduce poverty [4]. At present more than 20,000 households have been connected to solar home systems and SHP have been providing electricity to people living in rural and remote area [5]. According to Government's strategy is to raise the national electrification rate to an ambitious target of 90% by the year 2020 [Appendix 1].Development of off-grid renewable energy sources such as SHP, solar, wind, biomass; increasing energy self-sufficiency and security; and implementation of power projects for maximum long-term sustainability including managing in sustainable ways for renewable energy sources.

In many years ago, electric power generation has been expended from 33 MW in 1975 (independent) to3,205 MW in 2012 as 99.8% from hydropower generation, 0.07% (1.51MW) from diesel generator and 0.02% (0.47MW) from Solar power and others. Currently the electrification ratio is approximately 82.25% (Appendix 1,3) and will be 90% in 2020 if the entire SHP plan are implemented and the existing plan are still running in full capacity (80% by grid plus 10% by off-grid) [6]. Therefore, the SHP will contribute for the off-grid supplies to remote areas where it is difficult to expand the present On-grid due to environment or cost reasons.

2. STATE OF PROBLEM

Most of the research agrees that the small hydro electric energy generation is environment friendly and it's very useful of generating the electricity in rural and urban area. The use of renewable sources is the most valuable solutions to reduce the environmental problems associated with fossil fuels based electric energy generation and achieve clean and sustainable energy development [7].

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The electric power sector is the government main development priorities in order to contribute for the rural electrification of 90% by the year 2020 nationwide (70% by 2010, 80% by 2015). Therefore, for reaching the target, government of Lao PDR is currently promoting the development of hydropower resources especially the Small hydro power for rural electrification.

But the main problems from rural electrification are: high initial investment with the rate of return, no actual tools for management and technical inspection standards. Currently, small hydropower development that provincial is responsible were not sustainable due to natural disaster, lack of management and lack of technical and budget for maintenance.

In term of SHP development, there are 5 stages to be considering such as: Preliminary survey, Basic plan survey, Implementation plan, Construction, O&M and Administration. In This research is to focus all stages by using the ESE model and try toimprove the project management to meet the target of sustainable development of Small Hydropower management in Lao PDR.

Fig.1. The 5 stages for small hydropower development

3. RESEARCH OBJECTIVES

The main purpose of research is to investigate the good management tools for small hydropower in rural area for the sustainable development also to improve the standard of living. This study is using the Economic, Social and Ecologicalblueprint model (ESE model) to identify the factors and creating methodology for trying to solve the problems in case of existing small hydropower that located from northern to southern of Lao PDR (Appendix 4)that provincial is responsible such as:

- To review concept of small hydropower development related to policy and strategy of GOL.
- To investigate of the small hydropower management methodology to take into account the new situation of development in rural area.
- To identify methodology with the suitable method of SHP management for rural electrification.

4. METHODOLOGY

In this study the main purpose is to analyze the 12 existing small hydropower projects in Lao PDR (with the capacity less than 5 MW) that was not sustainable. In thispaper willbeintroduced only the concept of the economyblueprint perspective that is one of the three perspectives in the ESE model for the sustainable small hydropower management in Lao PDR.

The method are separate into 2 procedures; first is the data collection and analysis of the 12 existing small hydropower projects in Lao PDR (with the capacity less than 5 MW, Appendix 2) that aren't sustainable by using the modified format fromMinistry of Energy and Mines, Lao PDR and ASEAN Energy Centre. Secondly, recommendation of the suitable management tools for sustainable and effectiveness management of small hydropower in rural area of Lao PDR by using the Economic, Social and Ecologicalblueprint model (ESE model).

In this paper will be introduced only the concept of the economyblueprint perspective that is one of the three perspectives in the ESE model for the sustainable small hydropower management in Lao PDR.

4.1 Data Collection and Analysis Method

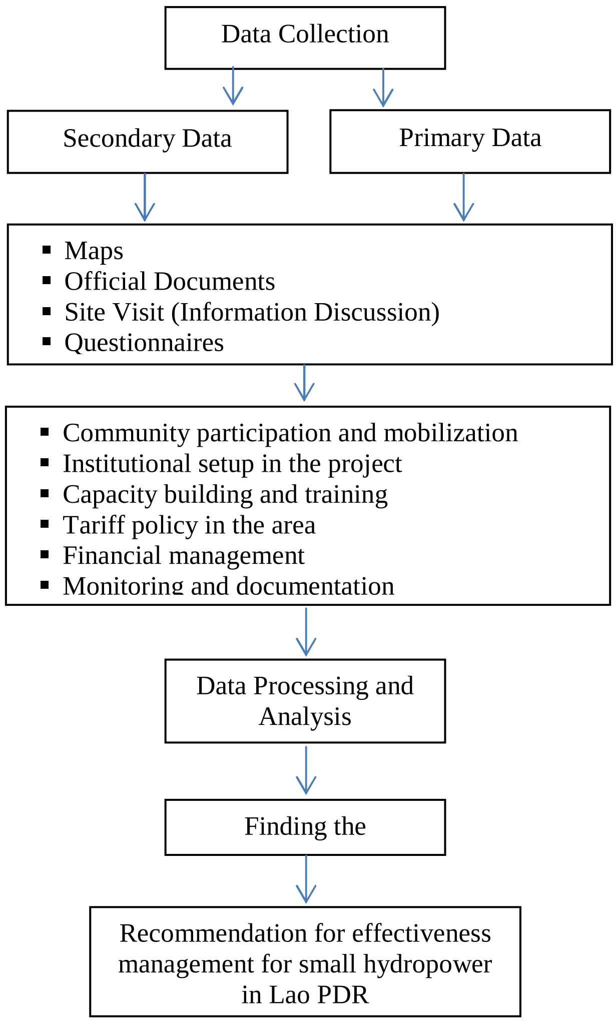

Fig. 2. Data collection and analysis method

4.1.1 Outcome of the data analysis

After using the modified format from Department of Policy and Planning, Ministry of Energy and Mines, Lao PDR and ASEAN Energy Centre to the existing 12 sample projects in to this study, we can identifies as the following:

- From the initial phase the participation from the community are very limited.
- Unclear of the responsibility between the local and central government.
- The over/less estimation of the project power generation.
- The unclear of the tariff policy.
- The low quality of the project's electric equipment
- Income can't cover the operation and maintenance
- Drop of power supply in dry season can not meet the power demand
- Lack of financial management mechanism.
- Lack of technical skill and educated staffs, because qualified staff is crucial for a sustainable operation of the plant.

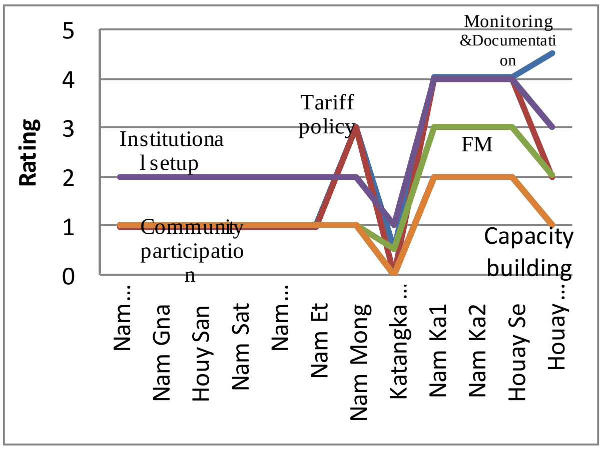

Fig. 3. The outcome of the 12 projects analysis

As shown in the graph that all 12 project have difficulty on the community participation and capacity building for the staff in the project. The projects that have more score on the questionnaire are Nam Mong, Nam Ka1&2 and Houay Se due to these projects is already connected to the EDL's grid. Therefore, the monitoring, tariff policy, institutional setup and financial management are already in place.

In conclusion, the project that responsible by PDEM are clearly having problem in mentioned areas as indicated in the analysis graph.

4.2 ESE model procedures

In general the Sustainable development of the hydropower sector is founded on 3 important principles namely:

- Economic sustainability relies upon the maintenance of the renewable resource base, and the use of non-renewable resource rents to support the development of other factor of production;
- Social sustainability is based upon the principles of inclusiveness, mutual understanding and consensus; and
- Ecological sustainability relies upon the avoidance of irreversible environmental impacts such as the loss of biodiversity, accumulation of persistent pollutants, or disruption of ecological cycles [17]

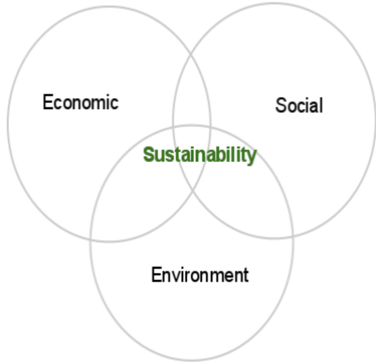

Fig. 4. The relationship of ESE

4.2.1 Economic Blueprint

4.2.1.1 General technical aspect

To create electricity in a small hydro power station the flow and head are the most important parameters for the design of a hydro power plant and following question are essential:

- How much water is available throughout the year for the turbine (flow)?
- What is the possible difference in height (head)?

Also the information which must be available is the general location and topography of the site and the distance to the potential electricity consumers and/or the closest power line near by.

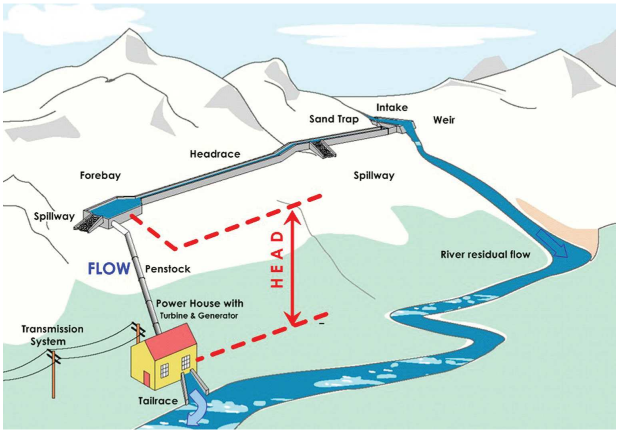

Fig. 5. Typical example of a diversion type run of river hydropower plant

4.2.1.2 Measure and Collect river flow and head data

The flow measurement has to be taken everyday during one full year. Depending on the size of the river there are different methods to measure such as bucket method, float method, current meter method (velocity-area-methods), sharp crested weir method and salt concentration method

For hydropower design it is very important to have flow data over as many year as possible to be sure how much water (in rainy and dry season) is available to run a turbine. These data give the designer the basic information for the select of a turbine that works efficiently.

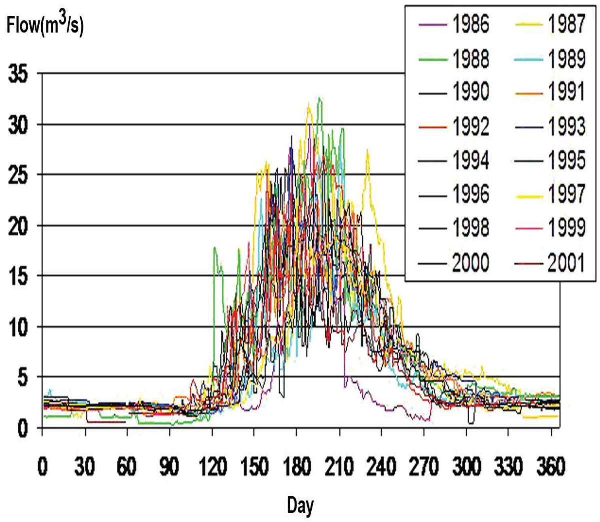

Fig. 6. Example of hydrographs for a 16 period

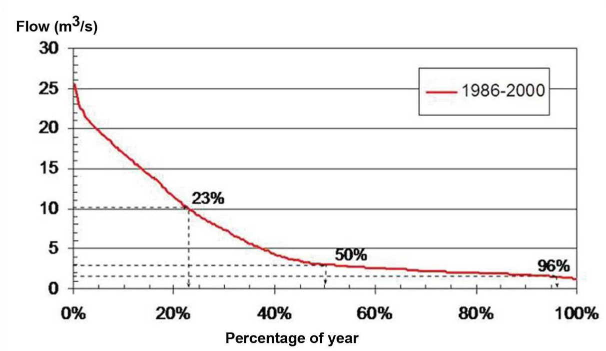

Fig. 7. Flow duration curve

The flow duration curve is generated by sorting all measured flow data size wise and printing them over 100% of the time covered by the measurements. The graph shown that during 23% of the time the discharge is high than 10 m3/s. this curve is the most important information for the design of the hydropower plant.

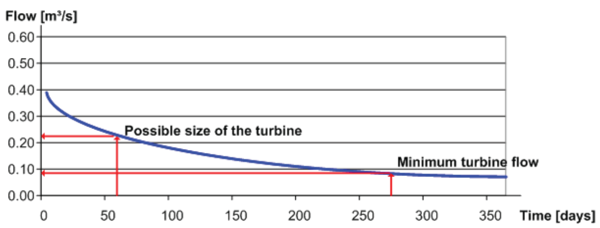

Fig. 8. Example of a flow duration curve for one year

The flow duration curve is generated from the river discharge curve by sorting all the 365 values. Based on the flow duration curve, the designer evaluates the available capacity.

Also, the Flood peak water level (height) should be estimated at the proposed powerhouse location. Thus, the site shall be selected with full confidence that frequent flooding (submergence) of powerhouse would not occur. Creager's flood curve method as described below. This method might be applicable to estimate design floods in the regional areas where no flood data is available.

The Creager's equation is given by the following formula:

$$Q_q = 46 \times C \times A^{a-1} \quad (1)$$

$$a = 0.894 \times A^{-0.048} \quad (2)$$

where

Q_q: Specific peak discharge (cubic ft/sec/square mile)

C: Creager's coefficient (40 for 100 yrs, 30 for 50 yrs)

A: Catchment area (square mile)

The unit conversions for feet and mile are as follows:

$1\ ft^3 = 0.02832\ m^3$

$1\ km^2 = 0.3861\ mile^2$

Head measurement is the difference in height between the water level of the planned forebay and the planned position of the turbine shaft there are different methods to measure such as water level, pressure gauge, barometer/altimeter, clinometer and level instrument.

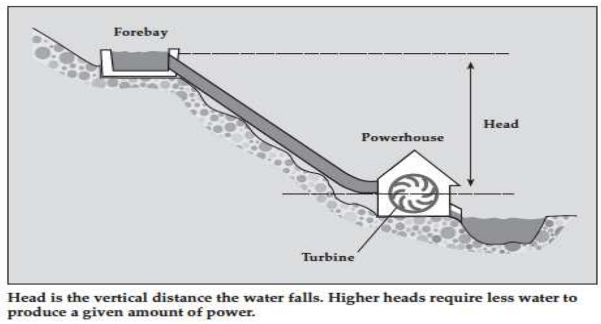

Fig. 9. General layout of Small Hydropower project

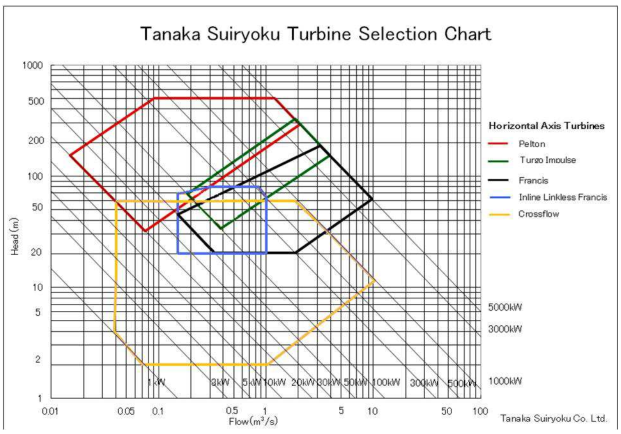

Fig. 10. Tanaka Suiryoku turbine selection chart

Table 1. Example of total expenditure

Target Village	X	Y	Z	Average
Firewood	10	12	14	12
Kerosene/Diesel Lump	12	12	12	12
Candle	14	14	16	14.7
Dry cell Battery	10	12	12	11.3
Private Diesel Genset	20	0	14	11.3
Electricity Tariff	0	0	0	0
Others	10	14	12	12
Total Energy Expense	**76**	**64**	**80**	**73.42**
Total Expenditure	**760**	**800**	**800**	**786.66**
% of EnergyExpense	10%	8%	10%	9.3%

4.2.1.3 Calculation of possible hydro electrical power

As mention the minimum flow and head are the most important information, when is known the theoretical hydro power is calculate as the following:

$$P[W] = Q[m3/s] \times H[m] \times 9.81 \qquad (3)$$

where

P = Power in Watt

Q = Minimum available flow

H = Head, difference in height in meter

This formula shows the hydraulic capacity only and refers to 100% efficiency without losses. Losses in penstock, turbine, gear transmission, generator and electricity transmission reduce the final electrical power. By calculating losses of 20-30%, the final electrical power will approximately be:

$$P[W] = Q[m3/s] \times H[m] \times 7 \qquad (4)$$

4.2.2 Energy Tariff Policy

Goods and services purchased make up household expenditure, while household consumption is defined as household expenditure plus the value of own produced goods taken out from households' own production. The difference in two concepts is basically caused by own produced rice and other crops, and meat/egg of own domesticated Livestock.

Consumption is importantto know living standard of household, and is utilized for judging poor and non-poor household in Laos. The target village should have the survey on the total expenditure such as food, education, medical, transport, energy because is important data to know capability of household for paying electricity tariff.

4.2.2.1 Ability To Pay (ATP) for electricity

Firstly we should calculate thetotal expenditure of the target villages than fine out the percentage of energy expenditure among the total expenditure.

For Example: The target villages are X, Y, Z and the total average expenditure is 786.66 and the percentage of average energy expense is 9.3%

According to the “Lao PDR Institutional Development for Off-grid Electrification”,the off-grid householdswere spendingabout l0% of their income on electricity and other lightingsources. The EDL Tariff Studyof SPRE II, also mentioned that electricity price should not exceedabout 10%of the householdincome.Judging from these conditions, ability to pay for electricity is assumed to be 5% - 10% ofhouseholdexpenditure.

4.2.2.2 Willingness To Pay (WTP) for Electricity

Contingent Valuation Method (CVM) is a method of estimating the value that a person placed on a good. The approach asks people to directly report their WTP to obtain a specified good, rather than inferring them from observed behaviors in regular market places.

In general there are 2 payments for accessing to electricity such as connection fee and monthly electricity tariff that depends on kWh.

Setting the Bid Prices (BP)

The bid prices used for the Survey in the target villages including the poor and non-poor strata were prepared base on pre-test of interview survey, price of alternative energy sources, and existing electricity tariff. The connection free and electricity tariff should agreed by 80% of households in the target villages.

The BP for the connection fee shouldn’t exceed the connection fees by the ADB’s Northern Area Rural Power Distribution Project in Lao PDR which is US$65.

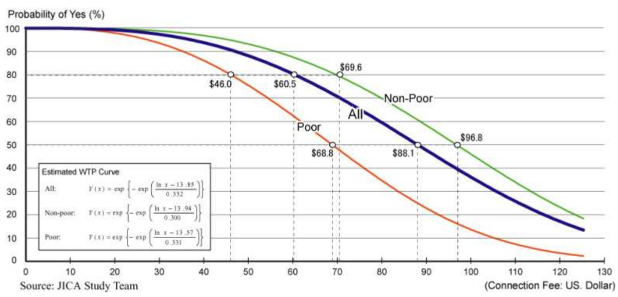

Fig. 11. Setting the willingness to pay tariff

The BP for the Electricity Tariff should compare to the Electricity Du Lao (EDL)’s residential consumer category tariff (US¢ 1.1 for 0- 50 kWh/month, US¢ 2.6 for 51- 150 kWh/month, and US¢ 7.4 for above 150 kWh/month) and also should compare with the existing electricity tariff of isolated diesel generator gird.

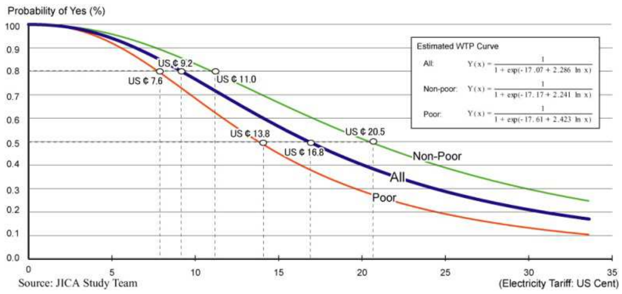

Fig. 12. Setting the connection fee

As show in the graph the connection fee and electricity tariff is the value at the intersection of the WTP curve and vertical line of 80% indicate that 80% of household have willingness to pay against the bid price [9].

4.2.3 Subsidy System for Hydropower

Financial assistance to the hydropower plant construction cost.

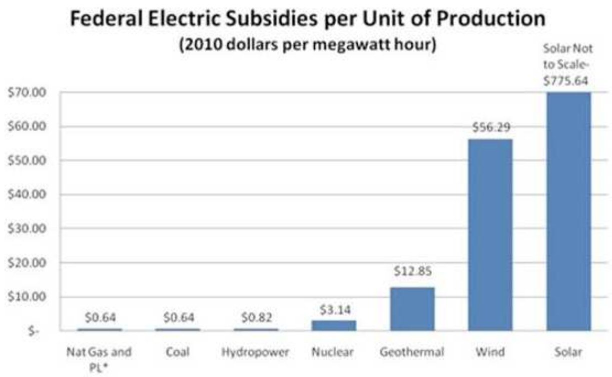

Fig. 13. Electricsubsidiesperunitofpreduction *[8]*

For example: in Japan the subsidy system are:

Table 2. Example of subsidies system in Japan

Scale	*Subsidy rate*
5MW-30MW	within 1/10
1MW-5MW	within 2/10
-1MW (Local government)	within ½
-1MW (Others)	within 1/3

4.2.4 Feed-In Tariff (FIT)

Model structure is that in each scenario calculates the electricity production and total costs of CSP plants and HVDC transmission installations on a yearly basis. Final outputs are total investment costs, total electricity to grid, and average annual levelized electricity costs, used to calculate feed-in tariff rates.

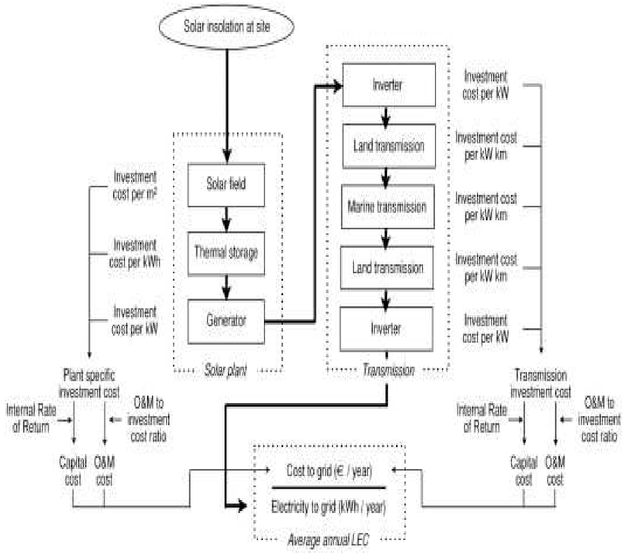

Fig. 14. FeedintariffstructureforSolarsystem *[10]*

The Japanese experiences for the new scheme of Feed-in Tariffs for renewable energy electricity since July 2012.

Table 3. Example of feed in tariff in Japan case

Feed-in tariffs applicable on 1st July 2012 in Japan		
Sector	Duration (years)	Tariff (c€/kWh)
Wind	20	
<20 kW		55,9
>20 kW		22,3
Geothermal	15	
<15 MW		40,6
>15 MW		26,4
Hydro	20	
<200 kW		34,5
200kW<P<1 MW		29,5
1MW< P <30MW		24,4
PV		
<10 kW for generated surplus	10	40,6
>10 kW	20	40,6
Biogas from sewage sludge and non fossil animal matter	20	39,6
Combustion of non fossile animal or plant matter	20	
Sewage sludge and municipal waste		17,3
Waste from cut wood		32,5
Hardwood		24,4
Construction waste		13,2

Source: METI

5. CONCLUSIONS

This paper study is using only the Economic blueprint perspective from the ESE model (Economic, Social and Ecologicalto solve the problems in the case of the existing small hydropower that located from northern to southern of Lao PDR.

Also this study will contribute to the new small hydropower in the future in term of sustainable management from the economic perspective.

As we have been discussed that the first component to focus on is the general technical aspect such as measure, collect river flow (flow duration curve)and head data is the must component for the planner to do in order to calculate the final electrical powerwith the losses of 20-30% (P[W] = Q[m3/s] x H[m] x 9.81), also the planner need to consider of the selected site with full confidence that frequent flooding (submergence) of powerhouse would not occur by using the Creager's method ($Q_q = 46 \times C \times A^{a-1}$) because over estimated of electrical power and damaging the powerhouse by flooded is one of the main problem for the small hydropower in Lao PDR.

The second component is energy tariff policy because for the project to cover the operation and maintaining cost the income form the electricity charges is the most important, and the tariff policy should include the setting up the ability to pay (ATP) for electricity and the study shown that the ability to pay for electricity is assumed to be 5%-10% of household expenditure. For the willingness to pay (WTP) for Electricity, in general there are 2 payments for accessing to electricity such as connection fee and monthly electricity tariff that depends on kWh and the detail is already discussed in the section 4.2.2.2. In addition, all tariff should agreed by 80% of households in the target villages.

The other component is also very important for the government to consider because from the analysis of the 12 existing small hydropower in Lao PDR shown that there are not any concrete incentive support from the government. Therefore, the subsidy system and feed in tariff is also an option for government to be considered.

Again this paper is using only economic blueprint perspective for the research and of cause there will be other 2 blueprints perspective namely; Social and Ecological to be study and combine it together for the sustainable management of small hydropower in Lao PDR.

ACKNOWLEDGEMENT

We would like to take this opportunity to thanks the Hydropower and Mining Technical Assistance's Project that funded by World Bank and AusAid for the supported of my research, and hopefully my research can contributed to the development of the small hydropower for rural electrification in Lao PDR in the future.

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APPENDIXS

Table A1. The Forecast ratio of electrify up to 2020

No	Plants Name	Province Location	Install capacity (kW)	Commercial Operation Date
1	Nam Boun 1	Phongsaly	110.0	1996
2	Nam Gna	Phongsaly	110.0	2010
3	Houy San	Huaphanh	110.0	1995
4	Nam Sat	Huaphanh	250.0	1999
5	Nam Phoune	Huaphanh	60	1995
6	Nam Et	Huaphanh	60	1995
7	Nam Mong	Luang Prabang	70	1996
8	Katang Kadeuang	Luang Prabang	3	N.A
9	Nam Ka1	Xieng Khuang	24	1999
10	Nam Ka2	Xieng Khuang	75	2002
11	Houay Se	Oudomxay	80	2003
12	Houay Samong	Attapeu	113.0	2003
Total			1,065.0	

Table A2. List of Existing SHP that responsible by Provincial

Description/Year	2005	2012	2020
Households	874,476	1,066,017	1,231,454
Households to be electrifies	508,799	189,255	1,108,309
In Percentage	58.2%	82.25%	90%
Population	5,900,000	6,256,197	7,261,600

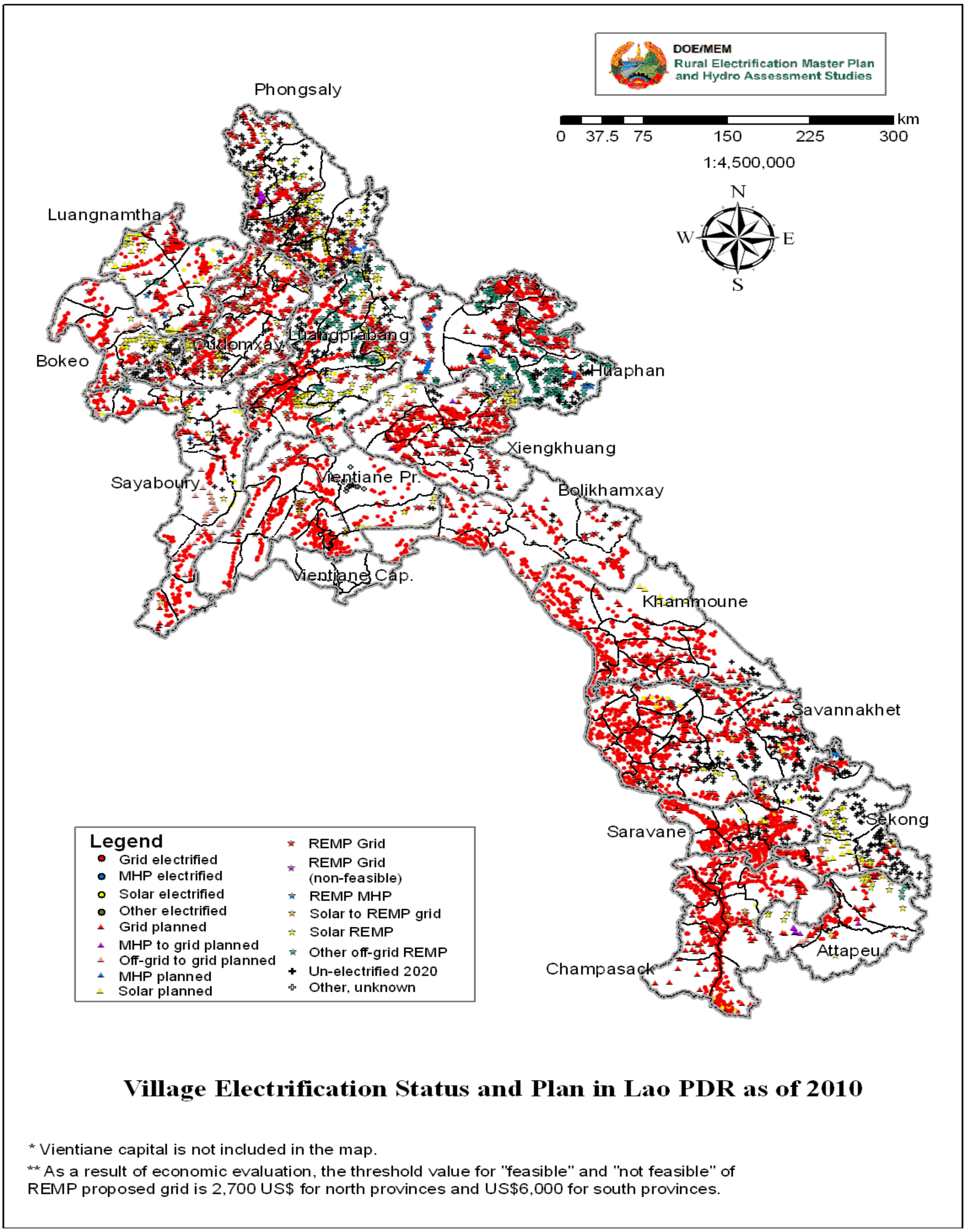

Fig. A1. Map of Village Electrification Status and Plan in Lao PDR

Fig. A2. 12 existing small hydropower project with the capacity less than 5 Mw in Lao PDR

Economic Dispatch with Multiple Fuels by Self-Organizing Hierarchical Particle Swarm Optimization

Le Dinh Luong, Le Anh Dung, and Vo Ngoc Dieu

Abstract— *This paper proposes a self-organizing hierarchical particle swarm optimization (SOH-PSO) algorithm for solving economic dispatch with multiple fuels (EDMF) problem. The PSO algorithm is simulating the behavior of birds or fish to find food. Each individual changes in velocity and position based on its experience improvement of itself and experience of both swarm. The PSO algorithm has been applied to solve many economic dispatch problems in power systems. In the new improved method, the conventional PSO algorithm is used with the variance coefficients to speed up the convergence to the global solution in a fast manner regardless of the shape of the cost function. The proposed SOH-PSO has been tested on various systems and the obtained numerical results have shown that the SOH-PSO method is more efficient and faster than many other methods reported in the literature for finding the optimal solution of EDMF. Therefore, the proposed SOH-PSO method can be a promising method for solving the practical EDMF problems.*

Keywords— **About four key words or phrases in alphabetical order, separated by commas.**

1. INTRODUCTION

The operation cost in power systems needs to be minimized at each time satisfying constraints via economic dispatch (ED) problem. In practical power system operation conditions, many thermal generating units, especially those units which are supplied with multiple fuel sources like coal, natural gas, and oil require that their fuel cost functions may be segmented as piecewise quadratic cost functions to represent for different types of fuel. The ED problem with piecewise quadratic cost functions is to minimize total fuel cost among the available fuels for each unit satisfying load demand and generation limits. This is a non-convex and complicated optimization problem since it contains the discontinuous values at each boundary forming multiple local optimal. Therefore, the classical solution methods are difficult to deal with this problem. One approach for solving the problem with such units having multiple fuel options is to linearization the segments and solving them by traditional methods [1]. A better approach is to retain the assumption of piecewise quadratic cost functions and proceed to solve them. A hierarchical approach based on the numerical method (HNUM) has been proposed in [2] as one way to approach to the problem. However, the major problem for the numerical methods is their exponentially growing time complexities for larger systems with non-convex constraints. Recently, many methods have been applied to solve the problem of multi-fuels economic dispatch as Genetic algorithm (GA), Evolutionary programming (EP), Nonlinear programming (NLP), Quadratic programming (QP), Tabu search (TS), Simulated Annealing (SA), Interior Point Methods (IP), Mixed Integer Programming (MIP)… However these methods are large number of iteration and easily influenced by parameters related controls. Recently, appeared PSO algorithm, this algorithm has several advantages compared to other methods of computational time faster and stable convergence. Scientists have applied PSO algorithm in many different areas of power system analysis such as system stability, coordination capacity… and has produced good results than other methods.

The purpose of this paper is to apply the advanced PSO algorithm to solve the problem of multi-fuel economic dispatch. Advanced PSO method is tested and confirmed by comparing results with other methods such as the numerical method (HNUM) [3], the Hopfield Neural Network (HNN) [4], Adaptive Hopfield Neural Network (AHNN) [6], Enhanced Lagrangian Artificial Neural Network (ELANN) [5], Improved Evolutionary Programming (IEP) [9], Modified Particle Swarm Optimization (MPSO) [11], Real Coded Genetic Algorithm (RCGA) [7], Hybrid Real Coded Genetic Algorithm (HRCGA) [7], Evolutionary Programming, Tabu search and Quadratic programming (ETQ) [10], Conventional Evolutionary Programming (CEP) [8].

2. PROBLEM FORMULATION

The main objective of EDMF problem is to minimize total cost of thermal power plants with many different fuels satisfying many different operating constraints including power balance and the limited capacity of the generating units. Therefore, it can be mathematically modeled with an objective function with equality and inequality constraints.

Consider a system with *N* plants and each plant

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generates a P_i MW of capacity. The capacity of plant should be scheduled so that the total cost F is minimized.

Mathematically, the problem is formulated as follows.

$$\text{Min } F = \sum_{i=1}^{N} F_i(P_i) \tag{1}$$

where the fuel cost function of each generating unit is represented by:

$$F_i(P_i) = \begin{cases} a_{i1} + b_{i1}P_i + c_{i1}P_i^2, \text{ fuel } 1, P_{i,\min} \le P_i \le P_{i1} \\ a_{i2} + b_{i2}P_i + c_{i2}P_i^2, \text{ fuel } 2, P_{i1} < P_i \le P_{i2} \\ \ldots \\ a_{ik} + b_{ik}P_i + c_{ik}P_i^2, \text{ fuel } k, P_{ik-1} < P_i \le P_{i,\max} \end{cases} \tag{2}$$

subject to

(1) Power balance constraint

$$\sum_{i=1}^{N} P_i - P_L - P_D = 0 \tag{3}$$

where the power loss is approximately calculated by Kron's formula (4):

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{i=1}^{N} B_{0i} P_i + B_{00} \tag{4}$$

(2) Generator operating limits

$$P_{i,\min} \le P_i \le P_{i,\max}\ ;\ i = 1,\ldots, N \tag{5}$$

where

$F_i(P_i)$	Fuel cost function of generating unit i
a_{ik}, b_{ik}, c_{ik}	Cost coefficients for fuel cost function k of unit i
B_{ij}, B_{0i}, B_{00}	Transmission loss formula coefficients
N	Number of online generating units
P_D	Total load demand of the system (MW)
P_L	Total network loss of the system (MW)
P_i	Output power of unit i (MW)
$P_{i,min}$, $P_{i,max}$	Lower and upper generation limits of unit i (MW)

With this formulation, the ED problem with multiple fuels becomes a non-convex optimization problem with multiple minima. For obtaining optimal solution for this problem, solution methods have to search for optimal solution in a very large search space, leading to time consuming. Therefore, it is necessary to limit the search space of the problem to reduce computational time, especially for large-scale systems.

3. SOH-PSO FOR EDMF

3.1 Conventional PSO

In PSO algorithm, the individual in the swarm approaches the target through its optimal speed, previous experience of itself and neighbor individual experience. In the search space of d-dimensional, position and velocity of individual i is described by vectors $X_i = (x_{i1},\ldots, x_{id})$ and $V_i = (v_{i1},\ldots, v_{id})$. $Pbest_i = (x_{i1}^{Pbest},\ldots\ldots, x_{id}^{Pbest})$ is the best location for the current instance i and $Gbest_i = (x_{i1}^{Gbest},\ldots\ldots, x_{id}^{Gbest})$ is the best location for the swarm.

Consider a swarm with p individuals in d-dimensional space. Position vector X_i^k of each individual i is updated by the following expression:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{6}$$

where V_i^{k+1} is a new velocity calculated by the formula:

$$V_i^{k+1} = \omega V_i^k + c_1 rand_1 \times \left(Pbest_i^k - X_i^k\right) + c_2 rand_2 \times \left(Gbest^k - X_i^k\right) \tag{7}$$

where

X_i^k	position of individual i at loop k
X_i^{k+1}	position of individual i in the loop k+1
V_i^k	velocity of individual i in the loop k
V_i^{k+1}	velocity of individual i in the loop k+1
ω	constant weight inertia
c_1	individual experience coefficient
c_2	coefficient of social relations of individual
$rand_1$, $rand_2$	random numbers between [0, 1]
$Pbest_i^k$	best position of individual i in the loop k
$Gbest^k$	best position of swarm in the loop k.

Expressions (6) and (7) show the principle search of PSO algorithm by using the change velocity and position of the individual. In particular, X_i^k is the position of individual i in loop k, we need to determine the position of individual i at the next loop X_i^{k+1}.

To determine X_i^{k+1}, the value of V_i^{k+1} needs to be calculated in advance. The vector V_i^{k+1} consists of three components. Firstly, ωV_i^k shows the inertial searching of the individual. During the search process, each individual tends to follow the inertia of the previous searches; Secondly, $c_1 rand_1 \times \left(Pbest_i^k - X_i^k\right)$ shows the individual experience based on the previous search, toward the best position $Pbest_i^k$; and lastly $c_2 rand_2 \times \left(Gbest^k - X_i^k\right)$ shows the ability to communicate by learning the best individual in the swarm, toward the best position of the swarm has been to present $Gbest^k$. Synthesis of the three-element vector above, the vector V_i^{k+1} is obtained for the velocity vector of individual i in the loop k+1. After obtaining the velocity vector V_i^{k+1}, it is combined with the position vector X_i^k at loop k to obtain the position vector X_i^{k+1} of individual i in the loop k +1.

3.2 PSO with time-varying inertia weight factor

The expression velocity vector update function of the individual is shown as follows:

$$V_i^{k+1} = \omega_{new} V_i^k + c_1 rand_1 \times \left(Pbest_i^k - X_i^k \right) + c_2 rand_2 \times \left(Gbest^k - X_i^k \right) \quad (8)$$

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{Iter_{\max}} k \quad (9)$$

$$\omega_{new} = \omega_{\min} + \omega \times rand_3 \quad (10)$$

where

ω_{max}, ω_{min} maximum and minimum inertia weight factors

k current iteration

$Iter_{max}$ maximum number of iterations

$rand_1$, $rand_2$, $rand_3$ random numbers in [0,1].

The function for updating the position remains the same as the basic PSO algorithm.

By experiment, Shi and Eberhart [1] found that the optimal solution can be improved by changing the inertia coefficient from 0.9 during the search to 0.4 at the end the search. The overall procedure of the PSO-TVIW is presented as follows:

Step 1: Created swarm includes all elements with position and velocity of the random *d*-dimensional search space.

Step 2: Calculate objective function value of each element.

Step 3: Comparing the objective function values of the elements to those from the previous iteration. For each individual, if the value of the objective function value at the current iteration is better than that from the previous iteration, the position corresponding to the current objective function is set to P_{besti}. Otherwise, the position in the previous iteration is set to P_{besti}.

Step 4: Recognize elements in the value swarm best objective function and objective function value assigned to the variable G_{best}. Store the values of P_{besti} and G_{best}.

Step 5: Change the velocity and position of the element by the expression:

$$V_i^{k+1} = \omega_{new} V_i^k + c_1 rand_1 \times \left(Pbest_i^k - X_i^k \right) + c_2 rand_2 \times \left(Gbest^k - X_i^k \right) \quad (11)$$

with:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{Iter_{\max}} k \quad (12)$$

$$\omega_{new} = \omega_{\min} + \omega rand_3 \quad (13)$$

$$X^{k+1} = X^k + V^{k+1} \quad (14)$$

Step 6: If the stopping criteria are not met, increase the iteration counter and return to Step 2. Otherwise, stop.

3.3 PSO with time-varying acceleration coefficients

PSO with time-varying acceleration coefficients (PSO-TVAC) is another improvement of the conventional PSO. In the PSO-TVAC, the experience factors of individual and society will change with respect to the number of iterations. The overall procedure of the PSO-TVAC is addressed as follows:

Step 1: Created swarm includes all the elements with position and velocity of the random d-dimensional search space.

Step 2: Calculate objective function value of each element.

Step 3: Comparing the objective function values of the elements to those from the previous iteration. For each individual, if the value of the objective function value at the current iteration is better than that from the previous iteration, the position corresponding to the current objective function is set to P_{besti}. Otherwise, the position in the previous iteration is set to P_{besti}.

Step 4: Recognize elements in the value swarm best objective function and objective function value assigned to the variable G_{best}.

Step 5: Change the velocity and position of the element in the expression:

$$V_i^{k+1} = \omega V_i^k + c_1 rand_1 \times \left(Pbest_i^k - X_i^k \right) + c_2 rand_2 \times \left(Gbest^k - X_i^k \right) \quad (15)$$

$$c_1 = (c_{1f} - c_{1i}) . \frac{Iter}{Iter_{\max}} + c_{1i} \quad (16)$$

$$c_2 = (c_{2f} - c_{2i}) . \frac{Iter}{Iter_{\max}} + c_{2i} \quad (17)$$

where c_{1f}, c_{1i}, c_{2f}, c_{2i} are constant inertias and

$$X^{k+1} = X^k + V^{k+1} \quad (18)$$

Step 6: If the stopping criteria are not met, increase the iteration counter and return to Step 2. Otherwise, stop.

3.4 PSO with Self Organizing Hierarchical

As we know, most of the improved PSO algorithm based on the linear change of the inertia coefficient and the penalty coefficient method. However, in some complex function, controlling the diversity of the population coefficient changes linearly inertia will cause the individual may soon converge to the optimal solution locally. Therefore, in this paper we proposed the improved PSO algorithm does not need the velocity of the previous iteration. We found this algorithm is simple but very effective when solving optimization problems for complex problems. The expression velocity vector update function of the individual is shown as follows

$$V_i^{k+1} = c_1 rand_1 \times \left(Pbest_i^k - X_i^k\right) + c_2 rand_2 \times \left(Gbest^k - X_i^k\right) \tag{19}$$

$$c_1 = (c_{1f} - c_{1i}).\frac{Iter}{Iter_{\max}} + c_{1i} \tag{20}$$

$$c_2 = (c_{2f} - c_{2i}).\frac{Iter}{Iter_{\max}} + c_{2i} \tag{21}$$

where c_{1f}, c_{1i}, c_{2f}, c_{2i} are constant inertias and

$$X^{k+1} = X^k + V^{k+1} \tag{22}$$

3.5 Implementation of SOH-PSO to EDMF

The objective function:

$$\text{Min } F = \sum_{i=1}^{N} F_i(P_i) \tag{23}$$

Neglecting transmission losses, power balance constraint

$$\sum_{i=1}^{N} P_i = P_D \tag{24}$$

By using the slack variable method, the capacity of the unit N is calculated as follow:

$$P_N = P_D - \sum_{i=1}^{N-1} P_i \tag{25}$$

The proposed SOH-PSO for the problem has been explained in detail in [2].

The overall procedure of SOH-PSO for the EDMF is as follows:

Step 1: Determine the number of plants in the power system. Determine the number of fuel of each plant, maximum capacity and minimum capacity of each plant, and the cost coefficient of each plant.

Step 2: Setting the initial parameters for the PSO algorithm: Number of individuals in the swarm, maximum number of iterations $Iter_{max}$, maximum and minimum inertia coefficient (ω_{max} and ω_{min}), maximum and minimum experience coefficient (c_{1i}, c_{1f}), maximum and minimum coefficient of social relation (c_{2i}, c_{2f}).

Step 3: Created position vector x_i and velocity vector v_i of the individual, with $i = 1, \ldots, d$ is the number of individuals in the swarm.

$$x_i = [\, P_{i1}, P_{i2}, \ldots, P_{i,n-1}, P_n \,]$$

$$v_i = [\, v_{i1}, v_{i2}, \ldots, v_{i,n-1}]$$

where P_{ik} is a generation capacity of the plant, with $k = 1, \ldots, n_i$ (n_i is the number of fuels for unit i). P_N is calculated by the expression (25).

Step 4: Calculated the total cost of fuel $F(x_i)$ with $i = 1, \ldots, d$. Calculated function fitness.

Step 5: Assigning value $Pbest_i = x_i$, find the value and position Gbest

Step 6: Setting loop $t = 1$

Take steps from 7 to 12 for each individual $i = 1, \ldots, d$

Step 7: Update v_{id}

Using expression (11), (12) and (13) if we want to use PSO TVIW method

Using expression (15), (16) and (17) if we want to use PSO TVAC method

Using expression (19), (20) and (21) if we want to use SOH-PSO method

Step 8: Update x_{id} by expression (6)

With i is number of plants and d number of individuals in the swarm

Check the limited capacity of the plants. If $x_{id} > x_{idmax}$ then $x_{id} = x_{idmax}$, if $x_{id} < x_{idmin}$ then $x_{id} = x_{idmin}$.

Step 9: Calculated value P_n by expression (25)

Step 10: Calculated total cost of the fuel $F(x_i)$ and update Pbesti, Gbest if objective function value is better than old objective function value

Step 11: Increase number of loop $t = t+1$

Step 12: Considering the conditions stop the program if $Iter > Itert_{max}$. Otherwise return to step 7

4. NUMERICAL RESULTS

To validate the effectiveness of proposed advanced PSO method, two improved PSO algorithm (PSO TVIW, TVAC PSO) was tested on 10 plant systems with different load demands and each plant has cost function including many quadratic to many different types of fuel. The results from these two methods were compared with HNUM [3], HNN [4], AHNN [6], ELANN [5], IEP [9], CEP [8], FEP [8], IFEP [8], MPSO [11], RCGA [7], HRCGA [7], and ETQ [10] for the load changes from 2400MW to 2700MW.

- *Setting parameter for algorithm PSO-TVIW*

Number of loop: $Iter_{max}=100$

Number of individuals in the swarm: d=20

Maximum acceleration coefficient: $\omega_{max}=0.9$

Minimum acceleration coefficient: $\omega_{min}=0.4$

Individual experience coefficient: $c_1=2.3$

The coefficient of social relations of individual: c_2=0.5

- *Setting parameter for algorithm PSO-TVAC*

Number of loop: $Iter_{max}$=100

Number of individuals in the swarm: d=20

Acceleration coefficient: ω=0.75

Minimum individual experience coefficient: c_{1min}=0.2

Maximum individual experience coefficient: c_{1max}=2.5

The minimum coefficient of social relations of individual: c_{2mim}=0.2

The maximum coefficient of social relations of individual: c_{2max}=2.5.

- *Setting parameter for algorithm SOH-PSO*

Number of loop: $Iter_{max}$=100

Number of individuals in the swarm: d=20

Minimum individual experience coefficient: c_{1min}=0.2

Maximum individual experience coefficient: c_{1max}=2.5

The minimum coefficient of social relations of individual: c_{2mim}=0.2

The maximum coefficient of social relations of individual: c_{2max}=2.5.

- The data system has 10 plant in following table

Table 1. The data of 10 plant system

Point	Branch	Fuel	a_i	b_i	c_i	P_{min}	P_{max}
1	1	1	26.97	-0.3975	0.2176	100	196
1	2	2	21.13	-0.3059	0.1861	196	250
2	1	2	1.865	-0.0399	0.1138	50	114
2	2	3	13.65	-0.1980	0.1620	114	157
2	3	1	118.4	-1.269	0.4194	157	230
3	1	1	39.79	-0.3116	0.1457	200	332
3	2	3	-2.876	0.0339	0.8035	332	388
3	3	2	-59.14	0.4864	0.1176	388	500
4	1	1	1.983	-0.0311	0.1049	99	138
4	2	2	52.85	-0.6348	0.2758	138	200
4	3	3	266.8	-2.338	0.5935	200	265
5	1	1	13.92	-0.0873	0.1066	190	338
5	2	2	99.76	-0.5206	0.1597	338	407
5	3	3	-53.99	0.4462	0.1498	407	490
6	1	2	1.983	-0.0311	0.1049	85	138
6	2	1	52.85	-0.6348	0.2758	138	200
6	3	3	266.8	-2.338	0.5935	200	265
7	1	1	18.93	-0.1325	0.1107	200	331
7	2	2	43.77	-0.2267	0.1165	331	391
7	3	3	-43.35	0.3559	0.2454	391	500
8	1	1	1.983	-0.0311	0.1049	99	138
8	2	2	52.85	-0.6348	0.2758	138	200
8	3	3	266.8	-2.338	0.5935	200	265
9	1	3	14.23	-0.0182	0.6121	130	213
9	2	1	88.53	-0.5675	0.1554	213	370
9	3	3	14.23	-0.0182	0.6121	370	440
10	1	1	13.97	-0.0994	0.1102	200	362
10	2	3	46.71	-0.2024	0.1137	362	407
10	3	2	-61.13	0.5084	0.4164	407	490

Case study 1

In this example, load demand is 2400MW.

Table 2. Costs and Processing Time

Method	Minimum Cost ($)	Maximum Cost ($)	Average Cost ($)	Time (s)
PSO TVIW	481.7226	485.1255	481.7566	0.33
PSO TVAC	481.7226	487.9564	481.7922	0.34
SOH- PSO	481.7226	484.1453	481.7468	0.31

Table 3. Costs and Capacity of Plant

Method	Plant	2400 MW			
		P_i(MW)	Fuel	Branch	Cost
PSO TVIW	1	189.746	1	1	481.7226
	2	202.341	1	3	
	3	253.901	1	1	
	4	233.044	3	3	
	5	241.855	1	1	
	6	233.046	3	3	
	7	253.269	1	1	
	8	233.041	3	3	
	9	320.375	1	2	
	10	239.381	1	1	
PSO TVAC	1	189.863	1	1	481.7226
	2	202.347	1	3	
	3	254.109	1	1	
	4	232.896	3	3	
	5	241.738	1	1	
	6	233.061	3	3	
	7	253.298	1	1	
	8	233.044	3	3	
	9	320.226	1	2	
	10	239.418	1	1	
SOH- PSO	1	189.608	1	1	481.7226
	2	202.272	1	3	
	3	253.987	1	1	
	4	233.013	3	3	
	5	241.892	1	1	
	6	233.139	3	3	
	7	253.252	1	1	
	8	233.065	3	3	
	9	320.178	1	2	
	10	239.595	1	1	

Table 4. Comparison of Total Cost and Processing time in Case 1

Method	P (MW)	Cost/hour($/h)	Time (s)
HNUM [3]	2401.2	488.50	1.08
HNN [4]	2399.8	487.87	60
AHNN [6]	2400	481.72	4
ELANN [5]	2400	481.74	11.53
IEP [9]	2400	481.779	-
MPSO [11]	2400	481.723	-
RCGA [7]	2400	481.723	49.92
HRCGA [7]	2400	481.722	6.1
ETQ [10]	2400	481.72	86.3
PSO TVIW	2400	481.7226	0.33
PSO TVAC	2400	481.7226	0.34
SOH- PSO	2400	481.7226	0.31

Case study 2

In this example, load demand is 2500MW.

Table 5. Costs and Processing Time

Method	Minimum Cost ($)	Maximum Cost ($)	Average Cost ($)	Time (s)
PSO TVIW	526.2389	526.2427	526.24003	0.38
PSO TVAC	526.239	526.2545	526.2418	0.37
SOH- PSO	526.2388	526.242	526.23938	0.37

Table 6. Costs and Capacity of Plant

Method	Plant	2700 MW			
		P_i(MW)	Fuel	Branch	Cost
PSO TVIW	1	206.582	1	1	526.2389
	2	206.351	1	3	
	3	265.921	1	1	
	4	236.014	3	3	
	5	257.858	1	1	
	6	236.01	3	3	
	7	268.799	1	1	
	8	235.913	3	3	
	9	331.736	1	2	
	10	254.815	1	1	
PSO TVAC	1	206.415	1	1	526.239
	2	206.479	1	3	
	3	265.892	1	1	
	4	236.038	3	3	
	5	257.763	1	1	
	6	236.085	3	3	
	7	268.645	1	1	
	8	235.993	3	3	
	9	331.562	1	2	
	10	255.127	1	1	
SOH- PSO	1	206.627	2	2	526.2388
	2	206.432	1	3	
	3	265.803	1	1	
	4	236.056	3	3	
	5	258.02	1	1	
	6	235.96	3	3	
	7	268.769	1	1	
	8	235.982	3	3	
	9	331.435	1	2	
	10	254.917	1	1	

Table 7. Comparison of Total Cost and Processing time in Case 2

Method	P (MW)	Cost/hour($/h)	Time (s)
HNUM [3]	2500.1	526.7	-
HNN [4]	2499.8	526.13	60
AHNN [6]	2500	526.230	4
ELANN [5]	2500	526.27	12.25
IEP [9]	2500	526.304	-
MPSO [11]	2500	526.239	-
RCGA [7]	2500	526.239	49.92
HRCGA [7]	2500	526.238	6.1
CEP [8]	2500	526.246	0.495
FEP [8]	2500	526.262	0.394
IFEP [8]	2500	526.246	0.558
PSO TVIW	2500	526.2389	0.38
PSO TVAC	2500	526.239	0.37
SOH- PSO	2500	526.2388	0.37

Case study 3

In this example, load demand is 2600MW.

Table 8. Costs and Processing Time

Method	Minimum Cost ($)	Maximum Cost ($)	Average Cost ($)	Time (s)
PSO TVIW	574.3809	574.7441	574.5649	0.38
PSO TVAC	574.381	574.7453	574.5622	0.37
SOH- PSO	574.3808	574.7432	574.41714	0.37

Table 9. Costs and Capacity of Plant

Method	Plant	2600 MW			
		P_i(MW)	Fuel	Branch	Cost
PSO TVIW	1	216.597	1	1	574.3809
	2	210.962	1	3	
	3	278.38	1	1	
	4	239.075	3	3	
	5	275.285	1	1	
	6	239.295	3	3	
	7	286.194	1	1	
	8	239.053	3	3	
	9	343.294	1	2	
	10	271.865	1	1	
PSO TVAC	1	216.65	1	1	574.381
	2	210.976	1	3	
	3	278.52	1	1	
	4	239.116	3	3	
	5	275.56	1	1	
	6	239.019	3	3	
	7	285.821	1	1	
	8	239.225	3	3	
	9	343.322	1	2	
	10	271.79	1	1	
SOH- PSO	1	216.544	2	2	574.3808
	2	210.886	1	3	
	3	278.342	1	1	
	4	239.102	3	3	
	5	275.598	1	1	
	6	239.162	3	3	
	7	285.677	1	1	
	8	239.176	3	3	
	9	343.497	1	2	
	10	272.016	1	1	

Table 10. Comparison of Total Cost and Processing time in Case 3

Method	P (MW)	Cost/hour($/h)	Time (s)
HNUM [3]	2599.3	574.03	-
HNN [4]	2599.8	574.26	60
AHNN [6]	2600	574.37	4
ELANN [5]	2600	574.41	9.99
IEP [9]	2600	574.473	-
MPSO [11]	2600	574.381	-
RCGA [7]	2600	574.396	37.57
HRCGA [7]	2600	574.38	5.4
PSO TVIW	2600	574.3809	0.38
PSO TVAC	2600	574.381	0.37
SOH- PSO	2600	574.3808	0.37

Case study 4

In this example, load demand is 2700MW.

Table 11. Costs and Processing Time

Method	Minimum Cost ($)	Maximum Cost ($)	Average Cost ($)	Time (s)
PSO TVIW	623.8092	623.8997	623.82531	0.38
PSO TVAC	623.8092	623.8353	623.8133	0.37
SOH- PSO	623.8092	623.8353	623.81199	0.37

Table 12. Costs and Capacity of Plant

Method	Plant	2700 MW			
		P_i(MW)	Fuel	Branch	Cost
PSO TVIW	1	218.23	1	1	623.8092
	2	211.707	1	3	
	3	280.84	1	1	
	4	239.669	3	3	
	5	278.513	1	1	
	6	239.679	3	3	
	7	288.456	1	1	
	8	239.58	3	3	
	9	428.554	1	2	
	10	274.772	1	1	
PSO TVAC	1	218.266	1	1	623.8092
	2	211.609	1	3	
	3	280.864	1	1	
	4	239.648	3	3	
	5	278.159	1	1	
	6	239.614	3	3	
	7	288.786	1	1	
	8	239.633	3	3	
	9	428.411	1	2	
	10	275.012	1	1	
SOH-PSO	1	218.393	2	2	623.8092
	2	211.733	1	3	
	3	280.698	1	1	
	4	239.683	3	3	
	5	278.474	1	1	
	6	239.451	3	3	
	7	288.529	1	1	
	8	239.405	3	3	
	9	428.596	3	3	
	10	275.036	1	1	

Table 13. Comparison of Total Cost and Processing time in Case 4

Method	P (MW)	Cost/hour($/h)	Time (s)
HNUM [3]	2702.2	625.18	-
HNN [4]	2699.7	626.12	60
AHNN [6]	2700	626.24	4
ELANN [5]	2700	623.88	21.36
IEP [9]	2700	623.851	-
MPSO [11]	2700	623.809	-
RCGA [7]	2700	623.809	44.56
HRCGA [7]	2700	623.809	6.47
PSO TVIW	2700	623.8092	0.38
PSO TVAC	2700	623.8092	0.37
SOH- PSO	2700	623.8092	0.37

The compared results from Table 2 to Table 13 show that the SOH-PSO has succeeded in finding a global optimal solution. The optimum active power is in their secure values and is far from the min and max limits. It is also clear from the optimum solution that the SOH-PSO easily prevent the violation of all the active constraints.

Tables 2, 5, 8 and 11 show the minimum, mean, maximum cost achieved by the SOH-PSO algorithm in 100 runs. Obviously, the minimum costs acquired by the proposed methods are all lower than that obtained HNUM [3], HNN [4], AHNN [6], ELANN [5], IEP [9], CEP [8], FEP [8], IFEP [8], MPSO [11], RCGA [7], HRCGA [7], and ETQ [10] in all cases. Total costs of the proposed method are close to those from the others for the rest cases. Note the power balance constraint in HNUM [3] and HNN [4] are not satisfied. These results show that the proposed methods are feasible and indeed capable of acquiring better solution. The optimal dispatches of the generators are listed in Tables 3, 6, 9 and 12. Also note that all outputs of generator are within its permissible limits.

5. CONCLUSION

In this paper, the self-organizing hierarchical particle swarm optimization (SOH-PSO) algorithm has been presented to solve the economic dispatch with multiple fuels (EDMF) problem. In the new improved method, the conventional PSO algorithm is used with the variance coefficients to speed up the convergence to the global solution in a fast manner regardless of the shape of the cost function.

Numerical results demonstrate that the SOH-PSO algorithm has more advantages for solving the EDMF than the previous methods in all the test case in terms of total costs and computational times. The results show that the proposed algorithm is efficient for solving nonconvex fuel cost functions. This paper is the first step in the study of EDMF function. A further direction for this study will be to apply other large-scale power systems with valve point effects.

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