Probabilistic Optimal Power Flow Considering Load and Solar Power Uncertainties Using Particle Swarm Optimization

Kanatip Rojanaworahiran and Keerati Chayakulkheeree*

Abstract— *This paper presents a probabilistic optimal power flow (POPF) considering probabilistic load and solar power uncertainties. The problem formulations were solved by particle swarm optimization (PSO). In the propose POPF problem formulations, the total cost minimization subproblem (TCMS) and the total real power loss minimization subproblem (TLMS) are solved by PSO, sequentially. In the POPF model, the probabilistic photovoltaic power plant (PVPP) and load data are integrated into the POPF computation. The propose POPF model has been tested with the IEEE 30 bus system and the probability density function (PDF) of power system variables are real power generator, total loss and total cost had been investigated. The results have shown that the POPF solutions obtained by PSO can determine the probabilistic optimal condition efficiently of power system operation. The method can be potentially applied to the high penetration of PVPP with uncertain load or other variables in the emerging power system.*

***Keywords*— Probabilistic optimal power flow, particle swarm optimization, probabilistic density function, probabilistic photovoltaic power plant, total cost minimization, total loss minimization.**

1. INTRODUCTION

Nowadays, countries around the world pay attention on the production electricity from solar energy because it is a renewable energy that inexhaustible and doesn't pollute to the environment. In Thailand, the photovoltaic power plant (PVPP) is also high penetrated and trended to be the dominant renewable energy in electricity generation Thailand is located near the equator, it receives constant and enough sunlight for electricity throughout the year. The statistics from the frame work of Thailand power development plan 2015-2036 (PDP2015) [1] said that the average annual of solar radiation in the country is 18.2 MJ/m2/day or 5.5 kWh/m2/day which high intensity of sunlight compared to many countries and satisfy for production in electricity include development, that why solar energy has a great influence for Thai people. After facing the high oil price issue in 1973 and 1979, solar energy became interested for developed countries and began to develop more seriously. According to Annual Report Department of Alternative Energy Development Plan Thailand 2015 (AEDP2015) [2] the renewables energy targeted on 20.3 percent of total energy in 2036. Hence, the renewable energy is the solution for electricity production in the future. The high potential renewable resources are solar energy, wind and bio-energy, the PDP2015 within 2036 has advert in Table. 1. In the Table. 1, the trend of solar energy production is increasing in the future.

The authors are with School of Electrical Engineering, Institute of Engineering, Suranaree University of Technology, 111, University Avenue, Suranaree, Maung, Nakhon Ratchasima, Thailand, 30000.

*Corresponding author: Keerati Chayakulkheeree; E-mail: keerati.ch@sut.ac.th.

Table 1. Alternative Energy Development Plan 2015

Type	Status on Dec 2015 MW	Target in 2021 MW	Target in 2036 MW
Biomass	2,726.60	3,940.65	5,570
Biogas	372.51	448.21	600
Wind	233.9	475.73	3,002
Solar Energy	1,419.58	2,993.29	6,000

In power system operation, the optimal power flow (OPF) is the most important and sophisticated problems. The objectives are minimizing total operating cost and total losses, subjected to power system constraints including power balance equations, real power generation and other power system constraints. In the past, many techniques have been used in OPF such as Particle Swarm Optimization (PSO) [3 -5], Ant Colony Optimization (ACO) [6] , Genetic Algorithm (GA) [7] and Tabu Search (TS) [8] . Amongst these stochastic optimization methods, PSO is a well-known technique base optimization presented by Dr. Eberhart and Dr. Kennedy in 1995 [9], inspired by social of behaviour of bird. PSO was demonstrated to be the best stochastic optimization methods for OPF problem.

Due to the weak linkage between real and reactive power in power system, real and reactive powers decomposition optimal power flow [10] is decoupled into the two subproblems are total cost minimization subproblem (TCMS) and the total real power loss minimization subproblem (TLMS). In the TCMS, the total generation cost minimization problem is solved by PSO, the optimal real power generator is the output. Meanwhile, in the TLMS, the total real power loss minimization problem is solved by PSO and the generator voltage magnitudes and transformer tapping are the outputs. The TCMS and TLMS are solved sequentially, for the lowest total generation cost of the system. The results on IEEE 30 buses system shown that the POPF can minimize the total cost and total real power loss effectively.

However, the electrical systems have been changed since the trend of electricity production using solar energy, then the common OPF can't represent uncertain factors in the power system like solar energy, load variation and other variables. So, the power system should consider the incorporate uncertainties in OPF modeling. Therefore, OPF problem is converted to the probabilistic optimal power flow (POPF) problem. In the several researches, POPF has many modeling are presented, such as [11-13] presented OPF model using probabilistic load and high uncertain power system model and show histogram of total power generation and real power generations obtained from Probabilistic distribution function (PDF). Meanwhile, [14-16] demonstrated OPF in Distribution Networks with high penetration of photovoltaic (PV) generation. [17-20] propose POPF wind farm forecasts with the incorporation of wind turbines production. Lastly, the paper [21] proposed Linear programing (LP) for solving the power generation dispatch with price-based real-time demand response (PRDR) represented by PDF,

In this paper, the POPF model considering uncertain load and PVPP real power generation has been presented. In the POPF model, the OPF is decomposed to TCMS and TLMS. The investigation is on Monte Carlo simulation (MCS) [22] and Normal PDF parameters estimation. The Normal PDF parameters estimation, the aggregated load and PVPP power generation PDF is obtained by MCS. The IEEE 30 bus system is used to test the proposed method.

The organization of this paper is as follows, the POPF problem formulations explained in Section 2. Meanwhile, MCS is illustrated in Section 3. Finally, the simulation results and conclusion are given in Section 4 and 5 respectively.

2. POPF PROBLEM FORMULATIONS

The probabilistic minimization total operating cost subproblem (a) and the real power loss minimization subproblem (b) are solved iteratively, and formulated as,

(a) minimize probabilistic total operating cost subproblem,

$$FC = \sum_{i=1}^{NG} F_i(\tilde{P}_{Gi}) \tag{1}$$

(b) and minimize the real power loss subproblem,

$$PL = \sum_{i=1}^{NB} \sum_{\substack{j=1 \\ j\neq i}}^{NB} P_{Lij}(V_i, V_j, T_{ij}), \tag{2}$$

subject to the power balance constraints,

$$\sum_{i=1}^{NG} P_{Gi} = (\tilde{P}_D - \sum_{i=1}^{VP} \tilde{P}_{vp}) + P_{losses}\ , \tag{3}$$

$$P_{Gi} - \tilde{P}_{Di} + \tilde{P}_{VP} = \sum_{j=1}^{NB} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_{ij}), i = 1,..., NB, \tag{4}$$

$$Q_{Gi} - \tilde{Q}_{Di} + \tilde{Q}_{VP} = -\sum_{j=1}^{NB} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_{ij}), i = 1,..., NB, \tag{5}$$

and line flow limit and transformer loading constraints,

$$| f_i | \le f_i^{\max}, i = 1,..., NL \tag{6}$$

and real power generation, bus voltage limit, and transformer tap limit constraint,

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \text{ for}, i = 1,\ldots, NG \tag{7}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \text{ for}, i = 1,\ldots, NB \tag{8}$$

$$T_i^{\min} \le T_i \le T_i^{\max} \text{ for}, i = 1,\ldots, NT \tag{9}$$

where,

FC	the total system operating cost ($/hr.),
$F(P_{Gi})$	the operating cost of the generator connected at bus *i* ($/hr.),
$f_i^{\max}$	the maximum line flow *i* (MVA),
f_i	the line flow *i* (MVA),
G_{ij}	the conductance of the lines between bus *i* and bus *j* for *j≠i*,
NG	the number of generators,
NB	the number of buses,
NT	the number of transformers,
NL	the number of transmission line,
PL	the real power loss (MW),
$\tilde{P}_{PV}$	probabilistic real power of photovoltaic (MW)
P_{Di}	demand at bus *i* (MW),
$\tilde{P}_{Gi}$	probabilistic demand (probabilistic) at bus i (MW),
$\tilde{P}_{Di}$	probabilistic demand (probabilistic) at bus *i* (MW),
P_{Gi}	the real of power generator connected bus *i* (MW),
$P_{GI}^{\max}$	the maximum real power generation at bus *i* (MW),
Q_D	reactive power demand at bus *i* (MVAR),
$\tilde{Q}_{Di}$	probabilistic reactive power demand at bus *i* (MVAR),
PV	the photovoltaic power plant (MW),
$\|Vi\|$	the voltage magnitude of bus *i* (*p.u.*),
V_i	the voltage of bus *i* (*p.u.*),
V_j	the voltage of bus *j* (*p.u.*),
$\|y_{ij}\|$	the magnitude of the y_{ij} element of Y_{bus} (mho),

θ_{ij} the angle of the y_{ij} element of Y_{bus} (radian) and

δ_{ij} the voltage angle difference between bus i and j (radian).

3. MONTE CARLO SIMULATIONS FOR POPF

MCS is a popular technique used to any uncertainty problem, the MCS helps visualize or the potential consequences to have better idea regarding the risk of a decision. In this paper, the MCS used in OPF with the combined uncertain load and PVPP. The computational procedures are explained as follow,

Step 1: Obtain load PDF and PVPP power generation PDF data at the dispatch hour,

Step 2: Set the average total power generation at i = 0 to zeros ($P_{AV}^{0}=0$) and set iteration i = 1,

Step 3: Solved OPF using POPF, at iteration i, with the sampling load PDF and PVPP PDF.

Step 4: Record the solution, such as real power generators, total cost and total loss.

Step 5: Does the iteration reach the maximum number of iterations? If yes, go to step 7. If no, go to step 3

Step 6: Compute the average total power generation obtained from iterations 1 to i,

Step 7: All solutions are used to fit for PDF parameters,

Step 8: Stop.

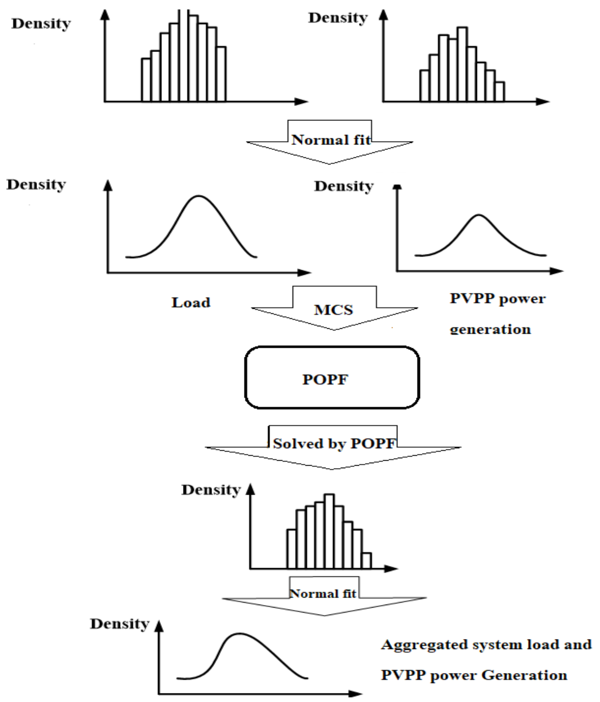

Fig.1. The POPF computation.

In this paper, a normal PDF used for random of the possible outcomes along with their corresponding probability variables. In normal PDF, the value of a random variable tends to be close to a certain value (mean value), the PDF is like a bell shape. In this paper the normal PDF used for load and PVPP PDF in POPF solution. The combined load and PVPP power generation PDF is obtained by MCS explained in Fig. 1. The computation procedure of POPF can be explained as follow,

Step 1: Define a domain of input for load and PVPP power generation.

Step 2: Generate inputs randomly from a probability distribution over the domain.

Step 3: Solved OPF by using POPF with inputs obtained in step 2.

Step 4: Aggregate the results.

Step 5: stop.

4. SIMULATION RESULTS

The POPF was simulated on IEEE 30 bus system, loads and PVPP power generation characteristic was obtained by the historical load of Thailand. The simulation also considering optimal placement study for PVPP placement and explained in 4.1. Lastly the POPF solution for IEEE 30 bus demonstrate in 4.2.

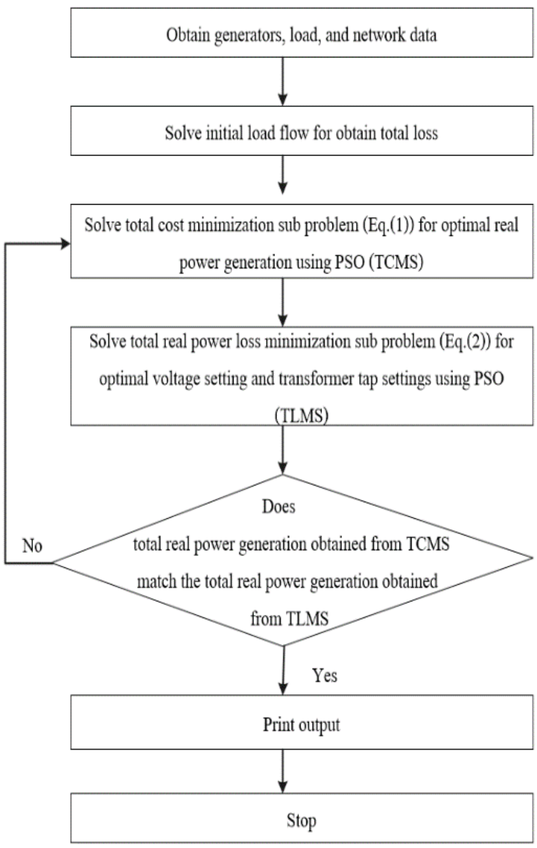

Fig 2. PSO computation.

4.1. Optimal solution using PSO

In the OPF problem formulation, the objective function can be expresses as two problems which are (1) total cost function and (2) total real power loss fucntion, the procedure illustrates in Fig 2. This paper, PSO has been used on the IEEE 30 buses featured in Fig 3. The system line data and bus data were obtained from [23]. The results compared to the methods in the previous works, are shown in Table 2.

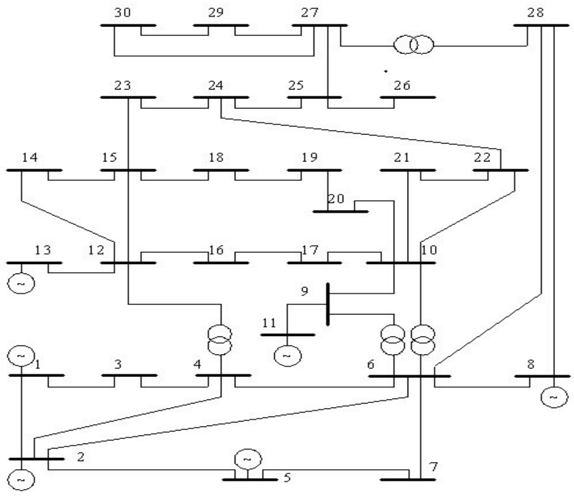

Fig 3. IEEE 30 Buses Test System.

Table 2 The comparison results for IEEE 30 buses

Variables (*p.u.*)	[8] (*p.u.*)	[3] (*p.u.*)	Proposed PSO (*p.u.*)
V_1	1.1000	-	1.0700
V_2	1.0482	-	1.0500
V_5	1.0213	-	1.0210
V_8	1.0291	-	1.0320
V_{11}	1.0951	-	1.0880
V_{13}	1.0937	-	1.0750
T_1	0.9966	-	0.9890
T_2	0.9814	-	0.9770
T_3	0.9972	-	0.9420
T_4	0.9513	-	0.9750
P_{G1}	164.2380	175.6915	176.60100
P_{G2}	42.6251	48.6930	48.6070
P_{G5}	20.0760	21.4494	21.4830
P_{G8}	20.7573	22.7200	21.7500
P_{G11}	11.4343	12.2302	12.0770
P_{G13}	11.2000	12.0000	12.0000
Total Cost ($/hr.)	814.4100	802.0136	800.985
Total Losses (MW)	13.9600	9.3301	9.118

In the Table 2, the OPF resulted from the method in [8] is shown to be the highest value of 814.41 $/hr. Meanwhile the OPF resulted from the method in [3] is lower than [1] 802.0136 $/hr. However, the proposed OPF using PSO resulted is the lowest cost at 80.985 $/hr. The proposed OPF is used for POPF study in 4.3.

Table 3. Optimal placement of PVPP in IEEE 30 bus system

PV location bus	Total losses (MW)		
	No installation	PV 5 % of demand	PV 10 % of demand
1		9.5995	10.0644
2		9.1239	9.1306
3		8.9109	8.7292
4		8.7135	8.3185
5		8.3087	7.5611
6		8.5677	8.0118
7		8.3847	7.6999
8		8.5710	8.0267
9		8.5799	8.0362
10		8.6002	8.0818
11		8.5765	8.0396
12		8.7752	8.4868
13		8.7649	8.4924
14		8.6897	8.6521
15	9.1180	8.5259	8.0897
16		8.6818	8.4216
17		8.5739	8.1429
18		8.4472	8.1013
19		8.4192	7.9961
20		8.4464	8.0488
21		8.4815	7.9431
22		8.4786	7.9625
23		8.4688	8.1680
24		8.3964	7.9202
25		8.5286	8.2892
26		8.7456	N.A. *
27		8.5720	8.2129
28		8.5224	7.9650
29		8.5025	8.6334
30		8.3109	8.4011

* *line constraint limit violation*

4.2. Optimal placement study for PVPP

The POP focuses an optimization for optimal placement are comparative size and location of PVPP in power system. The objective function is reduction total real power losses, the optimal placement study tested by MATLAB software. The optimal placement results shown in Table 3.

In table 3, the optimal placement study result shown that bus 5 provide the minimum total losses among all bus with the total losses 7.5611 MW on installation PV 10% of demand. It is confirmed that the optimal placement location for PVPP is bus 5 evinced in Fig. 4 .

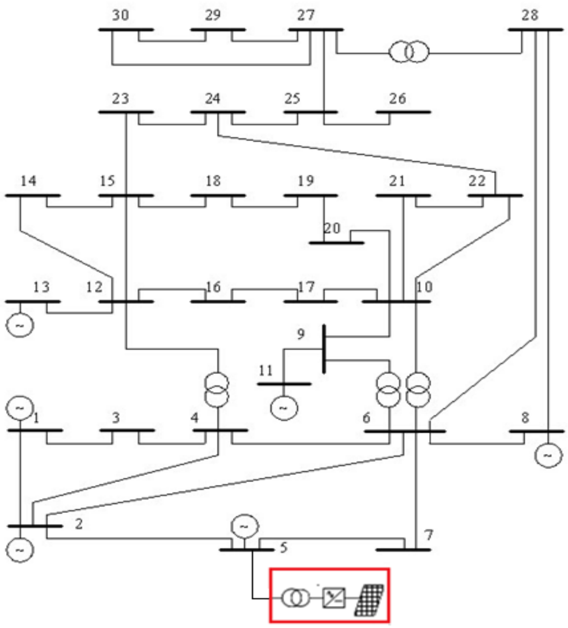

Fig. 4. The PVPP location.

4.3. POPF solutions for IEEE 30 bus system

In the simulation, the daily load profile on the peak day of Thailand is used. Meanwhile, the PVPP power generation characteristic is obtained from the solar power intensity in Nakornpathom. The PVPP and load power generation PDF results are indicated in Fig 5. and Fig 6.

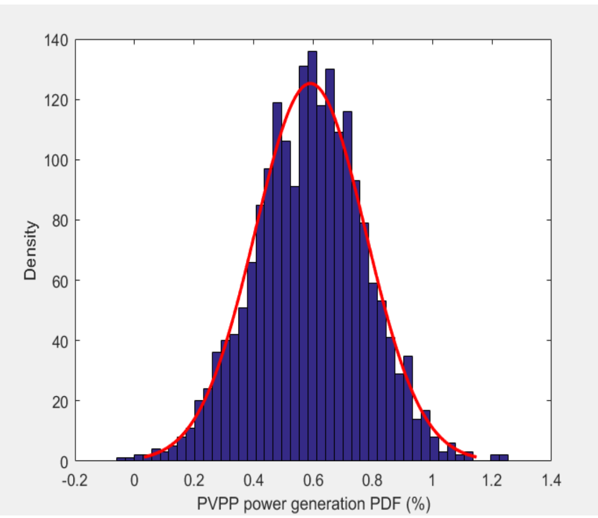

Fig. 5. Aggregated PVPP power generation PDF.

In Fig.5, the aggregated PVPP power generation PDF obtained by MCS resulted. The Mean is 0.59019 and Variance is 0.0345775. The results represent that the mean value of PVPP is very close of the middle of bell shape, that mean The PVPP power generation PDF is followed probabilistic theory.

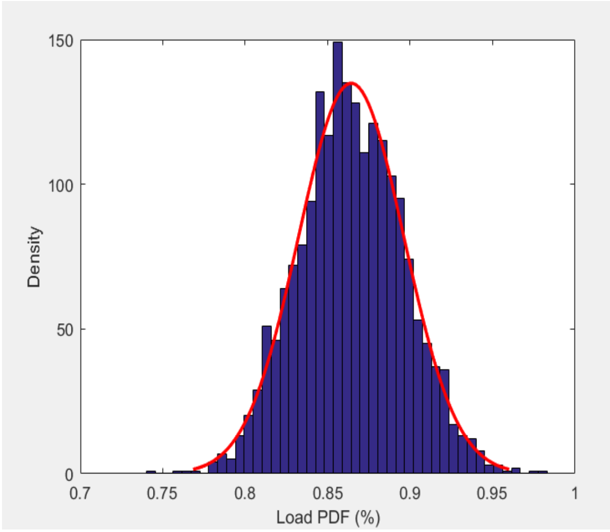

Fig.6. Aggregated Load PDF.

For the Fig. 6 the load profile of the peak day of Thailand at 2:00 p.m. of everyday is used. The load profile is transferred into the ratio of peak load, the aggregated load PDF gave the mean is 0.864219 and the variance is 0.0010197. The results shown that the variance is very low, so the aggregated load PDF is satisfied.

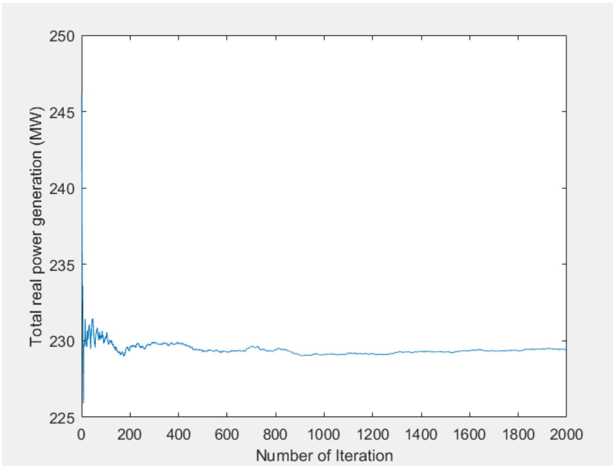

Fig. 7. Convergence of MCS.

In Fig. 7, the MCS solution with 2,000 iterations, meanwhile the solution was converted at less than 1000 iteration to the mean value of 230 MW. For the Normal parameters' estimation, the aggregated total cost and total losses PDF is obtained by MCS as shown in Fig. 8 and Fig. 9.

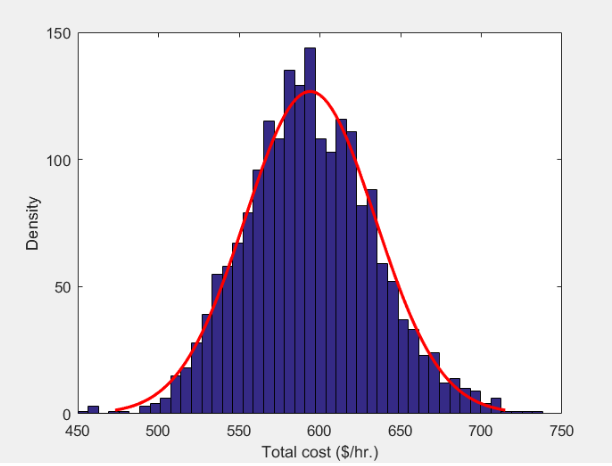

Fig. 8. Aggregated total cost PDF.

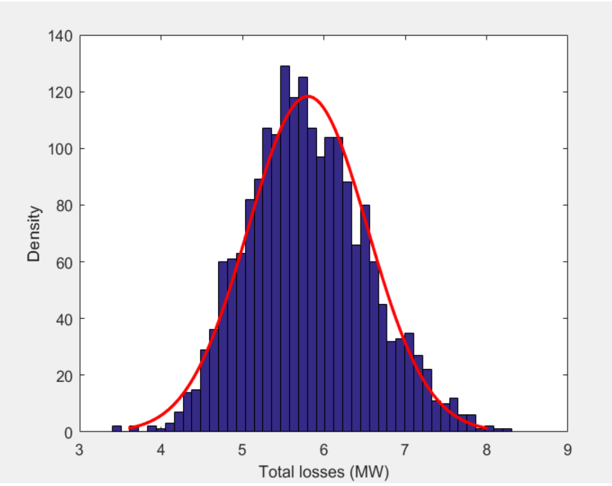

Fig. 9. Aggregated total loss PDF.

In Fig. 8, the mean of total cost by MCS simulated is 593.997 $/hr., meanwhile the variance is 1622.6. For the total cost histogram, the result shown that the shape is very flat cause high variance and breadth of answers.

Lastly, In the Fig. 9 the aggregated total loss PDF provided mean and variance are 5.80385 and 0.539995 respectively. The statistical parameter by POPF revealed in Table 4.

Table 4. The statistical parameter obtained from POPF

Variable	Mean	Variance
Total cost ($/hr.)	593.997	1622.6
Total losses (MW)	5.80385	0.539995
PVPP power generation (%)	0.59019	0.0345775
Load (%)	0.864219	0.0010197

5. CONCLUSION

In this paper, the POPF using normal distribution is proposed and investigated. The total real power loss and system operating cost can be minimized continually. The results have shown that the POPF can solve efficiently for the optimal solution. Therefore, the POPF can successfully define the POPF outputs, using Normal PDF.

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