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The study of reliability indices, power losses, and economic effects when distributed generators (DG) connected to a distribution system

Pathomthat Chiradeja [a], Chaichan Pothisarn [b], Atthapol Ngaopitakkul [b]

[a] *Faculty of Engineering, Srinakharinwirot University, Bangkok, Thailand*
[b] *Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand*

Abstract

The increasing of electrical energy demand around the world required more generation part of the power system. Distributed Generators (DG) provides electric power to a specific location near to the customers to avoid the unnecessary losses, e.g., transmission and distribution costs. Currently, distributed generators (DG) which are based on renewable energy technologies such as solar, wind, and biomass are widely applied in power system. However, the system reliability is the key factor for the electrical system installation. This paper presents a methodology for determining the reliability index and total electrical losses of the power system model used in Thailand performed by DigSILENT PowerFactory. Thus, the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Expected Interruption Cost (ECOST) are assessed as reliability indices, while the active and reactive power is considered as losses of the system. Moreover, the study and analysis of an economic impact on DG to determine the optimal size and type are investigated. The results indicate that the location and sizing of DG have a significant influence on the reliability indices and the power losses. The economic evaluation reviews that the biomass DG of 1 MW gives the best DPP (4.78 years) and IRR (25.27%), as well as more efficient in electrical generation than the solar power and wind power.

Keywords: SAIFI, SAIDI, distributed generator, renewable energy, power loss, economic

1. Introduction

In Thailand, Ministry of Energy and Provincial Electricity Authority (PEA) have encouraged private electricity producers to participate in the alternative energy generation, which carry out a policy to purchase electricity from renewable energy with the form of tariffs—Feed-in Tariff (FiT). From The increase in Very Small Power Producer (VSPP), which produces electricity from renewable energy, it is necessary to study the effects of power generation from renewable energy sources, which is represented by a distributed generator (DG), connected to distribution systems. The impact of DG installation on distribution systems has both advantages and disadvantages. For instance, DG can raise the voltage levels of loads, especially when DG is installed near large loads and far away from the power station. However, voltage compensation equipment needs to be adjusted appropriately and used in accordance with a power flow. Next, DG can reduce electrical losses in transmission lines and distribution systems if the size and position are reasonable. By contrast, if the size of DG is too large, maybe enhanced electrical losses occur in the system. Moreover, DG has still an effect on the protection system of both the distribution system side and power users, which make the fault being higher than normal conditions. Moreover, the setting of

* Manuscript received February 7, 2019; revised December 10, 2019.
Corresponding author. *E-mail address*: atthapol.ng@kmitl.ac.th.
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relays is more difficult, having a negative effect on DG disconnection out of the system too often.

There are numerous research studies on the installation of distributed generator. The work [1] proposed the algorithm finding the economic dispatch problem and designed the DG allocation strategy to instate the DG in suitable location in finite time. In [2], the authors formulated dynamically and automatically algorithm to find an optimal distributed energy resources coordination. In [3], in order to obtain the optimum size and locations of the system connected to multiple DG, the multi objective optimization for voltage regulation has been proposed. The residual current protection, effect of harmonic introduced by DGs and grounding location has been studied in [4] to find the optimal configuration of residual current protection in network with DGs.

System performance during normal and abnormal conditions has been analyzed in [5] considering different fault points in the system using short circuit and transient stability analysis to find the impact of DGs placement and sizing on ring distribution network. In [6], the optimization method has been evaluated using genetic algorithm for time varying loads, the optimum placement and appropriate size of DG has been obtained. The strategic DG placement by indices-based techniques has been introduced in [7] acquiring an improvement of the voltage stability, penetration level, power transfer capacity, and voltage profile. Critical clearing time determination and stability enhancement measurement has been studied in [8] to identify the major concern for system transient stability.

Authors in [9] present an adaptive scheme altering the protection system integrated DG, the simplified system simulated with ETAP and ATP/EMTP to evaluate the system efficiency. The optimum size and location of DG to reduce system losses has been introduced in [10] using MATLAB to implement single and multiple DGs aimed to reduce the losses within statutory limits. Simulation indicate the optimal power losses while satisfying the security constraints has been analyzed in [11] to achieve the energy efficiency improvement. In paper [11], a technique to identify the voltage validation when DG is connected to distribution systems is presented. The effect of reverse power flow from DG penetration using a constriction factor embedded local particle swar optimisation algorithm along with the appropriate particle formulation is conducted in [12]. Moreover, the analytical planning approach for determining the maximum penetration of DG is discussed in [13].

In this paper, the study and analysis of reliability indices and power losses as well as an economic impact of DC connected to 22 kV distribution system are investigated. This paper is organized as follow. Section 2 is system description. Section 3 presents reliability indices and power losses and the evaluation is dealt with in Section 4. Section 5 discusses economics analysis followed by the conclusion, which is given in Section 6.

2. System Description

The distribution systems of Provincial Electricity Authority (PEA) is comprehensive mainly electricity services in Thailand. Thus, reliability improvement and power loss reduction of the distribution system become important issues that need to take into the account when distributed generations— solar power, wind power, and biomass—are integrated to the systems. For this reason, the DIgSILENT PowerFactory software is used to simulate the PEA’s distribution systems and analyze these issues.

Fig. 1 shows the single-line diagram of the distribution system of the Thanyaburi substation in the Pathum Thani province. It covers 8.18 km of distribution line distance and has four BUS connected with DG. The data and parameters of the system which are distribution line distance, load positions, load sizes, group of users, and the number of users, are determined by the geographic information system of the PEA— total loads connected to the distribution system is 11.59 MW and 8.41 Mvar.

3. Reliability Indices and Power Losses

To make the desirability to customer, good services and minimum time of system interruption are main concerns for provider. The popular indices for system reliable confirmation are System Average

Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Expected Interruption Cost (ECOST) represent reliability indices, the calculations are described as follows:

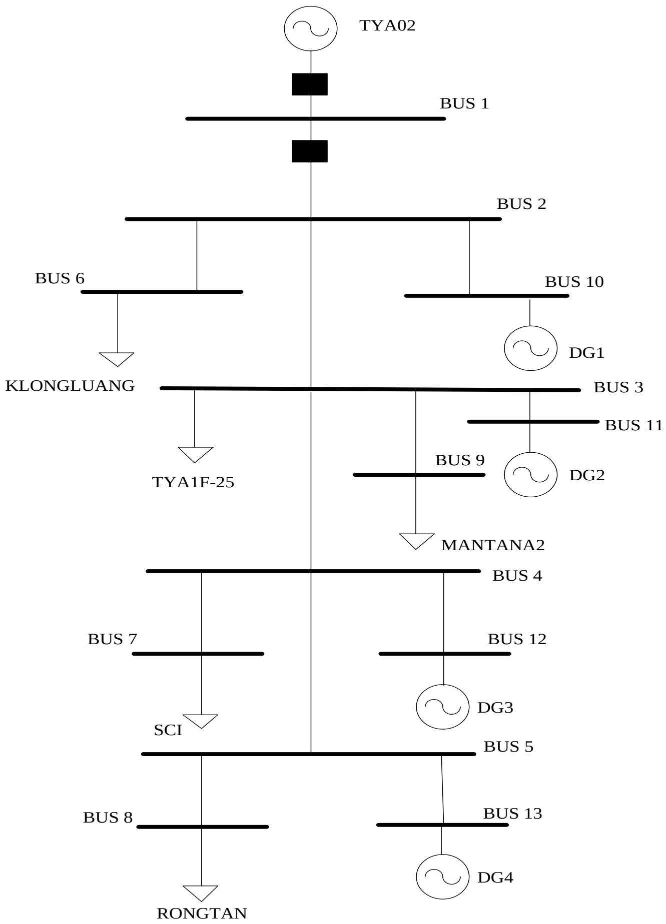


Fig. 1 The single-line diagram of the distribution system of the Thanyaburi substation

- System Average Interruption Frequency Index (SAIFI)

$$SAIFI = \frac{\sum_{i \in R} \lambda_i N_i}{\sum_{i \in R} N_i} \tag{1}$$

where:

λ_i is the failure rate or load interruption at node *i*.

N_i is the number of customers served at node *i*.

R is total customers at each node.

- System Average Interruption Duration Index (SAIDI)

$$SAIDI = \frac{\sum_{i \in R} U_i N_i}{\sum_{i \in R} N_i} \tag{2}$$

where:

U_i is the duration of load interruption at node *i* in a year.

- Expected Interruption Cost (ECOST)

$$ECOST = \sum_{k=1}^{NLP} \sum_{j=1}^{NC} L_{kj} f_j c(d_j) \quad (3)$$

where:

NLP is total number of considered loads.

NC is total number of outage leads to power interruption in load point *k*.

L_{kj} is load capacity interrupted at load point *k* of scenario *j* in kW.

f_j is interruption frequency of scenario *j*.

$c(d_j)$ *is outage cost in duration d of contingency* j.

The power losses of a distribution system can be calculated by using data from current magnitude resistance and reactance of branch. In addition, the active power loss (P_{loss}) and reactive power loss (Q_{loss}) in a distribution system can be formulated as follows

$$P_{loss} = 3I_i^2 R_i \quad (4)$$

$$Q_{loss} = 3I_i^2 X_i \quad (5)$$

where:

I_i is the current magnitude of branch *i*

R_i is the resistance of branch *i*

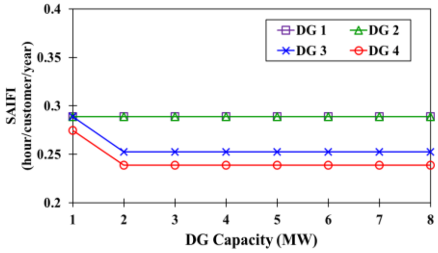
X_i is the reactance of branch *i*

4. Reliability Indices and Power Loss Evaluation

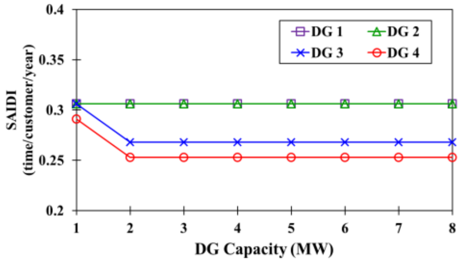
The power system used in this study is a representative 22 kV distribution system of Provincial Electricity Authority (PEA), which is presented in Fig.1. The network under investigation is modeled by the DigSILENT PowerFactory software to analyze the effects to system reliability indices and power losses when the system connected with DG.

In case study, the distribution generators: DG1, DG2, DG3, and DG4 at bus 10, 11, 12, and 13 respectively are simulated to evaluate reliability and power loss indices. The index results are used to compare with the case of without DG, which has the SAIFI of 0.288781 time/customer/year, the SAIDI of 0.306 hour/customer/year, the ECOST of 5,216 $/year, the P_{loss} of 0.15 MW, and the Q_{loss} of 0.28 Mvar. The results of reliability and power loss evaluation indices are shown in Fig. 2 and Fig. 3 respectively.

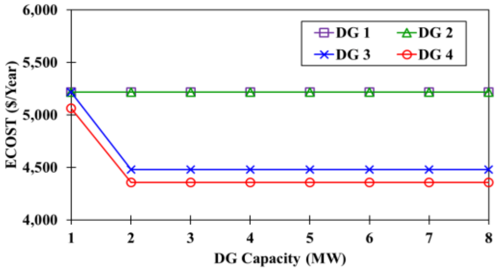
From Fig. 2(a) and 2(b), the SAIFI and SAIDI of the DG1 and DG2 provide the values equal to the case of without DG, which are 0.288781 time/customer/year and 0.306 hour/customer/year respectively. Since the DGs are installed near the substation, the effect of the failure rate or load interruption (λ_i), the number of customers (N_i), and the duration of load interruption (U_i) on the users is similar to the without DG case. The DG3 of 1 MW has the both SAIFI and SAIDI equal to the case of without DG. However, the DG3 of 2-8 MW has the trends of SAIFI and SAIDI to decrease with 0.252647 time/customer/year and 0.268 hour/customer/year respectively, as the number of users affected by the failure rate or load interruption (λ_i), the number of customers (N_i), and the duration of load interruption (U_i) have change to decrease. The DG4 is installed far from the substation, leading to the reduction of SAIFI and SAIDI according to the sizes of DG.



(a) SAIFI of DGs when the capacity are varied



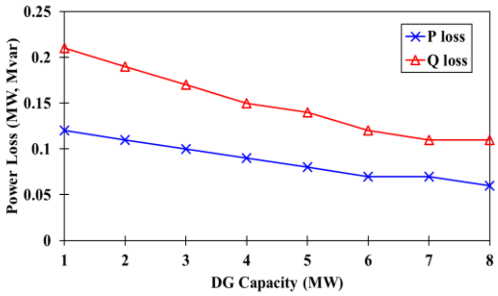
(b) SAIDI of DGs when the capacity are varied



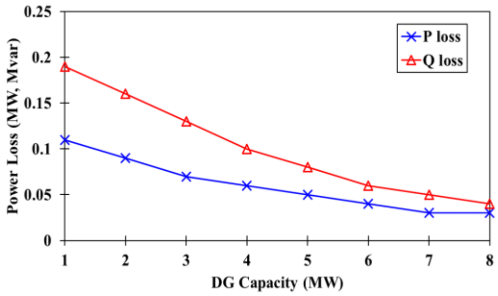
(c) ECOST of DGs when the capacity are varied

Fig. 2. The reliability indices of system connected to DGs

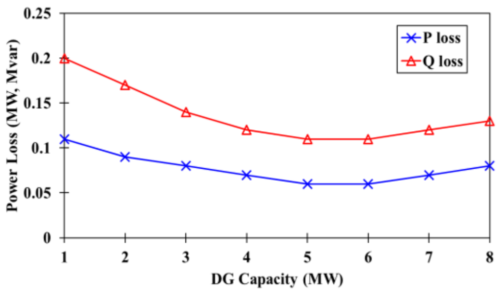
By observing Fig. 2(c), the total sizes of DG1 and DG2 provide the ECOST equal to the case of without DG with 5,216 $/year due to they located near the substation. The DG3 of 1 MW has the ECOST similar to the without DG case while the sizes of 2-8 MW have the trends of the ECOST to decrease with 4,480 $/year. For DG4, it is located far from the substation, decreasing in the values of interruption frequency f_j and load capacity interrupted (L_k). Hence, the ECOST decreased in every sizes.



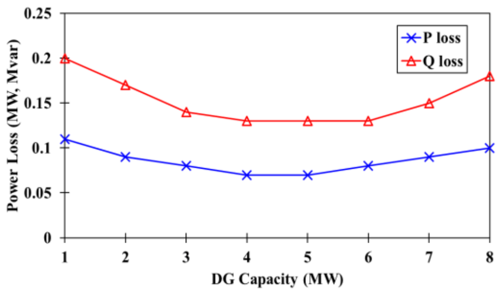
(a) P_{loss} and Q_{loss} of DG1



(b) P_{loss} and Q_{loss} of DG2



(c) P_{loss} and Q_{loss} of DG3



(d) P_{loss} and Q_{loss} of DG4

Fig. 3. P_{loss} and Q_{loss} of DG when the capacity is varide

By considering Fig. 3, The P_{loss} and Q_{loss} decreased by the size of the DG that is equal or close to the size of the load and installed on location that near the largest load. Because installation the DG near the largest load to cause the resistance and reactance of cable multiplied by the distance cable and give less valuable because of its length of conductor is the shortest distance and the current magnitude) I (is less as well. As a result, the P_{loss} and Q_{loss} are the fewest. Furthermore, the sources of the substation and the DG can support to supply the electrical energy to the load by distance, near or far and according to the electricity capacity. The distribution line is divided to supply load according each the generator. Therefore, the connected load is decreased, thus currents in cable) I (dropping quadratic forms and the distance of cable in the distribution system is shortened. Therefore, the total resistance and reactance of the cable is lowered accordingly.

5. Economic Evaluation

Economic analysis is used to evaluate the value of DG installation in distribution systems. Discount payback period (DPP) and internal rate of return (IRR) are used to be economic indicators. The DPP is a capital budgeting procedure used to determine the profitability of a project, which gives the number of years that takes to break even from undertaking the initial expenditure, by discounting future cash flows and recognizing the time value of money. The IRR is used to evaluate a project or investment. If the IRR of a new project exceeds a company's required rate of return, that project is desirable. If IRR falls below the required rate of return, the project should be rejected.

For economic evaluation of DG integration to the distribution system, results are presented in Table 1, Table 2, and Table 3 for the cases of solar power, wind power, and biomass respectively. For the indexes that indicate economic value, DPP and IRR are calculated based on investment costs of a project and total income in each year (i.e. electricity production and maintenance cost saving). For economic evaluation, the obtained DPP and IRR values are actually implemented by the Excel software. As a rule, the investment costs of solar power, wind power, and biomass are obtained from Energy Policy and Planning office (EPPO), Ministry of Energy in Thailand. The total income is assessed by revenues of electricity costs deducted from opportunity costs due to failure in system operation, hence having a blackout. For the revenues, they are electrical power can be produced in one year (annual energy production; AEP) multiplied by constant electricity purchase rates throughout the project life— Feed-in Tariff (FiT). In these case studies, the opportunity costs are calculated by a number of blackout (6 times per a year) multiplied by repair times (average 1.059109 hours per time), which is 6.35 hours per year. After that, this value is compared with a number of hours all year (8,760 hours), and then the compared value is multiplied by the revenues, which is the opportunity costs caused by power outage.

The economic evaluation results in the case of solar energy by varying the sizes from 1 to 8 MW are shown in Table 1. For instance, the solar power of 5 MW can produce electrical energy for 7,008,000 kW-hours per year. Therefore, the revenue carried out with the FiT of 0.174 US$ per kW-hours is 1,219,392.00 US$ per year. The investment cost of this project is 9,392,488.95 US$. By considering the opportunity cost from selling electricity to the PEA, there is power outage of 6.35 hours per year, leading to the opportunity cost of 882.85 US$ per year. Thus, total income is 1,218,509.15 US$ per year. The above calculated economic parameter values are used to evaluate the DPP and IRR based on equation (2), (3) and (7). For this reason, the solar power size of 5 MW has the 11.51 year DPP and 12.22 % IRR. By observing overall results, the solar power of 5, 6, 7, and 8 MW provides the best DPP which is 11.51 years and has the IRR of 12.22%, since the investment costs of the solar power sizes of 5, 6, 7, and 8 MW per megawatt, which is 1,878,497.79 US$ per MW, are lower than the other sizes of solar power.

For the case of wind power as shown in Table 2, the wind power sizes of 6, 7, and 8 MW can provide the best DPP at 14.92 years and have the IRR of 10%. However, the wind power sizes of 1, 2, 3, 4, and 5 MW have higher the DPP and lower the IRR than the former cases, since there are higher investment costs per megawatts. For this reason, the wind power installation of 6, 7, and 8 MW gives economic performance. In the cases of biomass economic evaluation results in Table 3, it is reviewed that 1 MW biomass allows for the best DPP of 4.78 years as well as the IRR of 25.27% which is more than the discount rate (7%), since there is higher a FiT (0.164 US$ per kW-hour) value than the other sizes of biomass.

Table 1. The economic evaluation parameters of solar power distributed generation

DG Type	Size (MW)	AEP (kWh/year)	CF (%)	Investment Cost ($)	FiT ($/kWh)	Revenue ($/year)	Opportunity Cost ($/year)	Total Income ($/year)	DPP (year)	IRR (%)
Solar Power	1	1,401,600	16	2,254,197.35	0.174	243,878.40	176.57	243,701.83	15.47	9.73
	2	2,803,200	16	4,257,928.33	0.174	487,756.80	353.14	487,403.66	14.02	10.48
	3	4,204,800	16	6,105,117.82	0.174	731,635.20	529.71	731,105.49	13.02	11.09
	4	5,606,400	16	7,764,457.54	0.174	975,513.60	706.28	974,807.32	12.09	11.75
	5	7,008,000	16	9,392,488.95	0.174	1,219,392.00	882.85	1,218,509.15	11.51	12.22
	6	8,409,600	16	11,270,986.75	0.174	1,463,270.40	1,059.42	1,462,210.98	11.51	12.22
	7	9,811,200	16	13,149,484.54	0.174	1,707,148.80	1,235.99	1,705,912.81	11.51	12.22
	8	11,212,800	16	15,027,982.33	0.174	1,951,027.20	1,412.56	1,949,614.64	11.51	12.22

Table 2. The economic evaluation parameters of wind power distributed generation

DG Type	Size (MW)	AEP (kWh/year)	CF (%)	Investment Cost ($)	FiT ($/kWh)	Revenue ($/year)	Opportunity Cost ($/year)	Total Income ($/year)	DPP (year)	IRR (%)
Wind Power	1	1,576,800	18	3,004,418.26	0.186	293,284.80	212.68	293,072.12	18.71	8.48
	2	3,153,600	18	6,008,836.52	0.186	586,569.60	425.36	586,144.24	18.71	8.48
	3	4,730,400	18	9,013,254.79	0.186	879,854.40	425.36	879,429.04	18.71	8.48
	4	6,307,200	18	12,017,673.05	0.186	1,173,139.20	425.36	1,172,713.84	18.71	8.48
	5	7,884,000	18	15,022,091.31	0.186	1,466,424.00	425.36	1,465,998.64	18.71	8.48
	6	9,460,800	18	15,960,972.02	0.186	1,759,708.80	425.36	1,759,283.44	14.92	10.00
	7	11,037,600	18	18,621,134.02	0.186	2,052,993.60	425.36	2,052,568.24	14.92	10.00
	8	12,614,400	18	21,281,296.02	0.186	2,346,278.40	425.36	2,345,853.04	14.92	10.00

Table 3. The economic evaluation parameters of biomass distributed generation

DG Type	Size (MW)	AEP (kWh/year)	CF (%)	Investment Cost ($)	FiT ($/kWh)	Revenue ($/year)	Opportunity Cost ($/year)	Total Income ($/year)	DPP (year)	IRR (%)
Biomass	1	6,132,000	70	3,958,026.51	0.164	1,005,648.00	728.82	1,004,919.18	4.78	25.27
	2	12,264,000	70	7,916,053.02	0.148	1,815,072.00	1,315.70	1,813,756.30	5.40	22.76
	3	18,396,000	70	11,874,079.53	0.148	2,722,608.00	1,973.55	2,720,634.45	5.40	22.76
	4	24,528,000	70	14,310,260.19	0.130	3,188,640.00	2,314.75	3,186,325.25	5.58	22.13
	5	30,660,000	70	17,887,825.23	0.130	3,985,800.00	2,893.44	3,982,906.56	5.58	22.13
	6	36,792,000	70	19,513,991.16	0.130	4,782,960.00	3,472.13	4,779,487.87	4.97	24.41
	7	42,924,000	70	22,766,323.02	0.130	5,580,120.00	4,050.82	5,576,069.18	4.97	24.41
	8	49,056,000	70	26,018,654.88	0.130	6,377,280.00	4,629.51	6,372,650.49	4.97	24.41

6. Conclusions

The summary of the study and analysis of reliability indices (SAIFI, SAIDI, and ECOST) and power losses (Ploss and Qloss) of DG connected to 22 kV distribution system shows that the location of DG which is far away from the power station causes the reliability index to be improved and significantly reduced (Increased reliability). On the other hand, the minimum reliability indices are where the location of the farthest DG from the substation. The reliability indices are likely to decrease as the size of DG increases. Especially in case of big capacity compared with load. The reliability index is significantly decrease. The DG installation location which is the closest to the largest load results the best improvement in power losses points of view, resulting a minimal active and reactive power losses. The power losses are reduced when the capacity of a DG is similar or close to the total load size.

From the economic analysis of the DG with different power ratings in the distribution system, the results show that solar power and wind power which are high power generation can be more achievable economic performance than low power one due to better the ratio between investment costs and MW. For instance, the solar power sizes of 5, 6, 7, and 8 MW provide the DPP of 11.51 years and 12.22% IRR and the wind power sizes of 6, 7, and 8 MW have the DPP of 14.92 years and 10% IRR, whereas the other sizes of solar power and wind power cause higher the DPP and lower the IRR, leading to low valuable investment. However, the biomass distributed generation of 1 MW gives the best DPP (4.78 years) and IRR (25.27%) due to the constant FiT which is high at 0.164 US$ per kW-hour as well as more efficient in electrical generation than the solar power and wind power.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Pathomthat Chiradeja, Chaichan Pothisarn, Atthapol Ngaopitakkul were Conceptualize the research. Chaichan Pothisarn, Atthapol Ngaopitakkul were conducted to the research. Pathomthat Chiradeja was Acquire the funding. Atthapol Ngaopitakkul was managed the project. Pathomthat Chiradeja, Chaichan Pothisarn wrote the paper. Atthapol Ngaopitakkul was rewrite and editing.

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