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An optimization model for distribution system planning integrated photovoltaic

V. V. Thang

Department of Electric Power Systems, Thai Nguyen University of Technology (TNUT), Vietnam.

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Abstract
A two-stage model for the optimal planning of distribution systems with the presence of photovoltaic generation system (PV) is presented in this paper. The proposed model can determine the optimal sizing and timeframe of the equipment (feeders and transformer substations) in distribution systems. Therefore, the optimal displacement, sizing, technology and installation period of PV are also determined. The objective function is minimizing the life cycle costs of the planning project. The technical constraints are used to guarantee the operability of the distribution system including AC power flow, feeder and substation upgrading section, limited of nodal voltage and PV capacity. The binary variables are also employed in the model to represent the cost function of the equipment as well as the investment and upgrade decisions. The algorithm is programmed in GAMS environment. The feasibility and effectiveness of the proposed model are examined in a 7-bus test system.

Keywords: Distribution systems planning; Photovoltaic (PV); Life cycle cost (LCC) and optimization.

1. Introduction
In the past decade, the planning of distribution systems had a major change due to the implementation of competitive electricity markets, DG technology and environmental pollution issues. In particular, DG that is directly connected to DS or directly supplying customers is used widely. These sources may employ various primary-mover technologies such as gas turbines, combined heat and power, fuel cells, wind turbines and photovoltaic. Therefore, the benefits of DG can be thought as the reduction of transmission and distribution cost, power loss and the enhancement of flexibility and reliability of DS, the improvement of differential voltage at nodes, as well as the reduction of environmental pollutions [1]. One of the DG technologies the most interested is PV and has been presented in many previous researches [2, 3]. However, PV requires high investments, increases the complexity of measurements and relay protection and the operation of DS [4]. In addition, PV uses renewable energy resources has power generation varying according to natural conditions.
Many planning models of the DG with different primary-mover technologies and PV in distribution systems have been researched and proposed. The authors in [5] presented a long-term DS planning model in order to determine the capacity, location for a new building investment process or upgrading the existing equipment by using the popular mathematical programming. The objective of the model is minimizing the total investment and operation costs of DG, the investment cost for feeder and substation transformers during the planning period. Another model in [6, 7] was proposed with the objective

function including the total investment and operation costs of DG, feeders and substation transformers upgrading costs, energy expenses and load's interruption costs. The objective function of the two-stage DS planning model in [8] is the minimization of total costs for upgrading feeders, substation transformers and DG construction, energy expenses purchased from markets and environmental pollution costs. Similarly, Ref. [9] introduced a DS planning model for determining the optimal equipment sizing and timeframe of DS. Besides, the model with the objective function of minimizing the life cycle cost for the distribution system planning was introduced in [10]. The model aims to find the best distribution system planning scheme to maximize the overall benefits and costs in the life cycle of the system. In previous studies, the output power of PV is always assumed to be constant without regarding to the natural variability which depends on the primary energy - this is of course far from reality. The power flow constraint usually uses DC model so the impacts of reactive power to the planning problem is ignored. Therefore, this paper proposes a DS optimal planning model that integrates the power output characteristics of PV, characteristics of load demand and electricity price. The AC power flow model is used to consider the influences of reactive power in DS planning. The detail about the planning model is illustrated in the following sections.

2. The mathematical model

In competitive electricity markets, DS are usually managed by distribution companies. These companies can buy electricity from wholesale markets or combine with the on-site PV in order to meet load demands. Therefore, the economic and technical measures of planning projects are changed which affects considerably to the duration, upgrading capacity of feeders and substations when PV are chosen in DS.

The proposed DS planning model is also executed in two stages. A MINLP model in the first stage is calculated and its results are fed into the second stage to obtain a comprehensive plan. The second stage receives information transferred from the first stage includes a set of decisions on location and period for equipments investment. Therefore, this model needs not use for binary variables and it is a NLP model. It should be noted that the energy production schedule obtained from the first stage is temporary and is revised in the next stage. The accuracy of the model is added in the second stage plan to more closely reflect the required investments and production schedules.

2.1 The mathematical model of the first stage

a) Objective function

The objective function of proposed model is to minimize the total life cycle cost of the investment project during calculation period as shown in [9] and is added with the part of reduced costs due to lower emissions. The total cost of objective function is calculated at the base year by equation $1/(1+r)^t$ with discount rate r as equation (1).

$$J = Min\sum_{t=1}^{T}\frac{1}{(1+r)^t}.\left(CF_t + CS_t + CPV_t + EPV_t + ES_t - TCO_t + RN\right) \quad (1)$$
$$\forall t \in T$$

where, the component CF_t is the upgrading costs of feeders for year t with fixed capital cost (C^{FF}) and the variable capital cost (C^{FC}) as shown in equation (2). The $\alpha_{ij.t}$ is the binary variable to represent the cost characteristic and decision variable for feeder upgrading is $F_{ij,t}$.

$$CF_t = \sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}(C^{FF}.\alpha_{ij,t} + C^{FC}.F_{ij,t}) \quad \forall ij \in N, i \neq j, t \in T \quad (2)$$

Similar to the above, the substation transformers upgrading costs in year t (CS_t) including fixed capital cost (C^{SF}) and variable capital cost (C^{SC}) is presented in equation (3). The $\gamma_{i.t}$ is a binary variable to represent the cost characteristic and decision variable for transformer upgrading is $\Delta S_{i,t}^S$.

$$CS_t = \sum_{i=1}^{NS}(C^{SF}.\gamma_{i,t} + C^{SC}.\Delta S_{i,t}^S) \quad \forall i \in N_S, t \in T \quad (3)$$

Electrical energy purchased cost from electricity markets (ES_t) is presented in equation (4).

$$\mathrm{ES}_t = \sum_{i=1}^{NS}\sum_{s=1}^{SS}\sum_{h=1}^{H} D_s.k_P.(\rho^S_{P.h}.P^S_{i,t,s,h} + \rho^S_{Q.h}.Q^S_{i,t,s,h}) \qquad (4)$$
$$\forall i \in N_S, t \in T, s \in SS,\ h \in H$$

The equation (5) is new investment costs in year t of PV. Beside, electrical energy purchased cost from electricity markets and costs for operation and maintenance of PV, operation season s and time h are shown in equation (6).

$$CPV_t = \sum_{i=1}^{N_{PV}} C_i^{PV}.P_{i,t}^{PV} \quad \forall i \in N_{PV}, t \in T \qquad (5)$$

$$EPV_t = \sum_{i=1}^{N_{PV}}\sum_{s=1}^{SS}\sum_{h=1}^{H} D_s.\rho_P^{PV}.P^{PV}_{i,t,s,h}\ \forall i \in N_{PV}, t \in T, s \in SS,\ h \in H \qquad (6)$$

The costs arising from emission taxes can be reduced due to lower emissions when PV using renewable energy resources are substituted for the traditional energies in DS (TCO_t). This part is negative and shown in equation (7) with ξ is emission coefficient of traditional energies and β is emission tax that may be enforced by the government.

$$TCO_t = \sum_{i=1}^{N_{PV}}\sum_{S=1}^{S_S}\sum_{h=1}^{H} \beta.\xi.D_s.P^{PV}_{i,t,s,h}\ \forall i \in N_{PV}, t \in T, s \in S_S, h \in H \qquad (7)$$

The residual value of equipments at the end of the planning period is presented in equation (8) and it is usually evaluated basic on the current market conditions. Hence, the residual value is the present value and it is calculated at base year in objective function.

$$RN_t = \frac{(t^F_{kh} - T_F)}{T_F}.CF_t + \frac{(t^S_{kh} - T_S)}{T_S}.CS_t + \sum_{i=1}^{N_{DG}} \frac{(t^{PV}_{kh} - T_{PV})}{T_{PV}} C_i^{PV}.P_{i,t}^{PV} \qquad (8)$$
$$\forall\, i \in N_{PV},\ t \in T$$

b) The constraints

**) Constraints for power flow*

The output power of PV fluctuates by solar radiation so it is also determined by time of the day and season in year. Hence, an AC nonlinear power flow model is used in this stage as represented in (9). With this constraint, the influences of reactive power to calculation power and voltage losses in DS are considered so results of proposed model are more accurate.

$$\begin{aligned} P^S_{i,s,t,h} - PD_{i,s,t,h} + P^{PV}_{i,s,t,h} &= \sum_{j=1}^{N} \left|Y_{ij,t}\right|.\left|U_{i,s,t,h}\right|.\left|U_{j,s,t,h}\right|.\cos(\theta_{ij,t} - \delta_{j,s,t,h} - \delta_{i,s,t,h}) \\ Q^S_{i,s,t,h} - QD_{i,s,t,h} &= -\sum_{j=1}^{N} \left|Y_{ij,t}\right|.\left|U_{i,s,t,h}\right|.\left|U_{j,s,t,h}\right|.\sin(\theta_{ij,t} - \delta_{j,s,t,h} - \delta_{i,s,t,h}) \end{aligned} \qquad (9)$$
$$\forall i, j \in N,\ s \in SS, h \in H, t \in T$$

where, $P^{PV}_{i,s,t,h}$ is the output power of PV that changes depending on the primary energy introduced in (10).

$$P^{PV}_{i,s,t,h} = P^{PV}_{i,t}.k^{PV}_{s,h} \qquad (10)$$

**) Capacity limited constraints of PV*

These constraints allow the selection of PV capacity in its limits at each node, and it ensures annually upgrading power corresponding to the equipment parameters as shown in (11).

$$0 \le P_{i,t}^{PV} \le P_{i,\max}^{PV}; \qquad P_{i,t}^{PV} = P_{i,t-1}^{PV} + \Delta P$$
$$\forall t \ge 1, i \in N_{PV}, t \in T \tag{11}$$

**) Upgrading section constraints of feeder*

The thermal limits are imposed to limit the loading of feeders and these limits are taken into the consideration of new feeder investments. Thus, the feeder upgrading constraints and upgrading power-satisfying equipment parameters are shown in (12). A step increase of feeder capacity at year t $(\Delta S_{\mathrm{ij},t}^{F})$ is set when the capacity value is equal or greater than the capacity limit used at year t-1.

$$S_{ij,t}^{max} \le (S_{ij,t-1}^{*F} + \Delta S_{\mathrm{ij},t}^{F}); \Delta S_{\mathrm{ij},t}^{F} \ge \Delta S_{\min}^{F}.\alpha_{\mathrm{ij,t}}; \qquad \Delta S_{\mathrm{ij},t}^{F} \le M.\alpha_{\mathrm{ij,t}}$$
$$\forall t \ge 1, ij \in N, t \in T \tag{12}$$

Then, the feeder capacity needs to meet in order to supply power to the load present in (13) and the upgrading section is selected by equation (14) with current density J.

$$S_{ij,t}^{*F} = S_{ij,t-1}^{*F} + \Delta S_{\mathrm{ij},t}^{F} \qquad \forall t \ge 1, ij \in N, t \in T \tag{13}$$

$$F_{\mathrm{ij},t} \ge \frac{S_{ij,t}^{*F}}{\sqrt{3}U_{dm}.J}.\alpha_{ij,t} \quad \forall t \ge 1, ij \in N, t \in T \tag{14}$$

**) Addition capacity constraints for substation*

These constraints allow to maximize the use of existing substations capacity and to satisfy upgrading power corresponding to the equipment parameters. A substation capacity addition step size $(\Delta S_{\mathrm{i},t}^{S})$ is used to set substation sizes as in equation (15) with the maximum and minimum allowable capacity which can be upgraded.

$$S_{i,t}^{max} \le (S_{i,t-1}^{*S} + \Delta S_{\mathrm{i},t}^{S}); \ \Delta S_{\mathrm{i},t}^{S} \ge \Delta S_{\min}^{S}.\gamma_{\mathrm{i,t}}; \qquad \Delta S_{\mathrm{i},t}^{S} \le M.\gamma_{\mathrm{i,t}}$$
$$\forall t \ge 1, i \in NS, t \in T \tag{15}$$

**) Constraints of nodal voltage limited*

The technical requirement constraints of limited nodal voltage are given in equation (16). The voltages at substation nodes are assumed constantly as equation (17).

$$U_{\min} \le \left|U_{i,s,t,h}\right| \le U_{\max} \quad \forall i \in N_L, s \in SS, t \in T, h \in H \tag{16}$$

$$\left|U_{i,s,t,h}\right| = cons\tan t \quad \forall i \in N_S, s \in SS, t \in T, h \in H \tag{17}$$

The decision variables of models include real and binary variables so calculation results must be corrected by the standard equipment in reality, and used as parameters in the second stage.

2.2 The mathematical model of second stage

This stage takes the input parameters obtained from the first stage as the additional capacity of substations, upgrading section of feeders, installation location and period of PV. Then, it determines the PV capacity within pre-defined bounds.

a) Objective function

The model has objective function similar to the first stage with upgrading variables of feeders $(F_{\mathrm{ij},t})$ and substations $(\Delta S_{\mathrm{ij},t}^{S})$ are replaced by the equipment parameters obtained from the first stage. Hence, the equations of objective function are presented as (18) and decision variable PV power is $P_{i,t}^{PV}$.

$$
\begin{aligned}
J_2 = Min\sum_{t=1}^{T}\frac{1}{(1+r)^t}.\Bigg(&\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}(C^{FF}.\alpha_{ij.t} + C^{FC}.F^*_{ij,t}) + \sum_{i=1}^{NS}(C^{SF}.\gamma_{i,t} + C^{SC}.S^{*S}_{i,t}) + \sum_{i=1}^{N_{PV}} C_i^{PV}.P_{i,t}^{PV} \\
&+ \sum_{i=1}^{NS}\sum_{s=1}^{SS}\sum_{h=1}^{H} k_s(\rho^S_{P.h}.P^S_{i,t,s,h} + \rho^S_{Q.h}.Q^S_{i,t,s,h}) + \sum_{i=1}^{N_{PV}}\sum_{s=1}^{SS}\sum_{h=1}^{H} D_s.\rho_P^{PV}.P^{PV}_{i,t,s,h} + \sum_{i=1}^{N_{PV}}\sum_{S=1}^{S_S}\sum_{h=1}^{H} \beta.\xi.D_s.P^{PV}_{i,t,s,h} \\
&+ \frac{(t^F_{kh} - T_F)}{T_F}.\sum_{i=1}^{N}\sum_{j=i+1}^{N} L_{ij}(C^{FF}.\alpha_{ij.t} + C^{FC}.F^*_{ij,t}) + \frac{(t^S_{kh} - T_S)}{T_S}.\sum_{i=1}^{NS}(C^{SF}.\gamma_{i,t} + C^{SC}.S^{*S}_{i,t}) + \sum_{i=1}^{N_{DG}} \frac{(t^{PV}_{kh} - T_{PV})}{T_{PV}} C_i^{PV}.P_{i,t}^{PV}\Bigg)
\end{aligned} \tag{18}
$$

$\forall ij \in N,\ t \in T, s \in SS, h \in H$

b) The constraints

**) Constraints for power flow and nodal voltage limited*

These constraints are similar to the first stage and presented on equations (9), (16).

**) Capacity limited constraints of feeder and substation*

To ensure the upgraded feeders are not overloaded by thermal limits, the load flow on feeder need satisfy as equation (19) and substation capacity must satisfy as equation (20).

$$S^F_{ij,t,s,h} \le S^F_{\max.ij,t} \qquad \forall t \ge 1, ij \in N, t \in T, s \in SS,\ h \in H \tag{19}$$

$$S^S_{i,t,s,h} \le S^S_{\max.i,t} \qquad \forall t \ge 1, i \in NS, t \in T, s \in SS,\ h \in H \tag{20}$$

**) Capacity limited constraints of PV*

The investment location and the period of PV were determined from the first stage so these constraints allow the selected PV capacity according to new limits as (21).

$$
\begin{aligned}
&0 \le P^{PV}_{i,t} \le P^{*PV}_{\max.i} \quad P^{PV}_{i,t} = P^{PV}_{i,t-1} + \Delta P \\
&\forall t \ge 1, i \in N_{PV}, t \in T
\end{aligned} \tag{21}
$$

The proposed comprehensive plan includes a MINLP model in first stage and NLP model in second stage. The calculation program is made in GAMS environment used MINOS solver [11] to find out an optimal solution. The parameters, symbols, variables sets and indices of model are presented in Tables 1-3.

3. Results and discussions

3.1 Diagram and parameters of distribution systems

A 7-bus and 22kV voltage radial diagram is investigated in this research as Figure 1 and is connected to 110kV transformer substation. The total active power and reactive power at the base year are 8838.0kW and 7309.2kVAR, respectively.

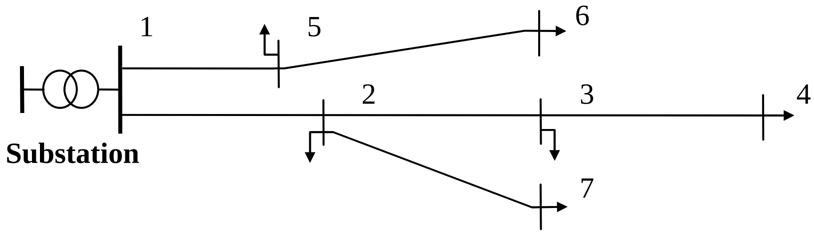

Figure 1. Diagram of test distribution system.

3.2 Assumptions in analysis

This research utilizes some economic and technical assumptions for the ease of computation:

- The planning period is 5 years and the annual developing rate of load demand is constant, 10% per year. At all of the load locations the typical characteristics of load demands for four seasons are assumed as Figure 2.

Table 1. Parameters.

No	Symbol	Definition	No	Symbol	Definition
1	r	Discount rate (%)	17	$S^{*F}_{ij,t}$	Maximum capacity need upgrading of Feeder (MVA)
2	C^{FF}	Fixed capital cost of Feeder ($/km)	18	ΔS^{F}_{min}	Capacity ramp-up limit for Feeder (MVA)
3	C^{FC}	Variable capital cost of Feeder ($/km.mm^2)	19	$S^{F}_{max.ij,t}$	Maximum capacity limit of standard Feeder (MVA)
4	$L_{i,j}$	Length of Feeder (km)	20	$S^{*S}_{i,t}$	Maximum capacity need upgrading of Substation (MVA)
5	$Y_{i,j,t}$, $\theta_{i,j,t}$	Magnitude and Angles of admittance matrix element (pu)	21	ΔS^{S}_{min}	Capacity ramp-up limit for Substation (MVA)
6	C^{SF}	Fixed capital cost of Substation ($/Substation)	22	$S^{S}_{max.i,t}$	Maximum capacity limit of standard Substation in planning year t (MVA)
7	C^{SC}	Variable capital cost of Substation ($/MVA)	23	J	Current density at thermal limit (A/mm^2)
8	C^{PV}_{i}	New investment cost for PV i ($/M)	24	M	Big number used maximum limit of variables in MIP and MINLP models
9	ρ^{PS}_{h}	Active power purchased cost from market ($/kWh)	25	U_{max}	Maximum voltage limit at bus (pu)
10	ρ^{QS}_{h}	Reactive power purchased cost from market ($/kVAh)	26	U_{min}	Minimum voltage limit at bus (pu)
11	$\rho^{DG}_{P.h}$	O&M cost of PV ($/kWh)	27	ΔP^{PV}	Active power ramp-up limit for PV (MW)
12	$PD_{i,s,t,h}$	Active power demand at bus (kW)	28	$k^{PV}_{s,h}$	Output power factor of PV
13	$QD_{i,s,t,h}$	Reactive power demand at bus (kVAr)	29	k_P	Variation factor of the price of electricity
14	$P^{PV}_{max.i}$	Maximum power limit of PV i (MW)	30	D_S	Total day per season
15	$P^{*PV}_{max.i}$	New maximum power limit of PV in second stage (MW)	31	ξ	Emission coefficient of traditional energies
16	$F^{*}_{ij,t}$	Standard section of Feeder in planning year t (mm^2)	32	β	Emission tax

Table 2. Sets and indices.

No	Symbol	Definition
1	N	Set of buses in distribution system
2	i, j	Bus (i, j $\in$ N)
3	N_L	Set of load buses in distribution system
4	N_S	Set of substation buses in distribution system
5	N_{PV}	Set of PV buses in distribution system
6	t, T	Planning year and overall planning period (t $\in$ T)
7	h, H	Hour and hours per day (h $\in$ H)
8	s,SS	Season and total seasons in year (s $\in$ SS)

Table 3. Variables.

No	Symbol	Definition
1	$F_{ij,t}$	Upgrading section of Feeder (mm^2)
2	$\Delta S^{S}_{i,t}$	Addition capacity for Substation (MVA)
3	$P^{PV}_{i,t}$	New investment capacity of PV (MW)
4	$P^{S}_{i,s,t,h}$	Active power purchased from electricity market (kW)
5	$Q^{S}_{i,s,t,h}$	Reactive power purchased from electricity market (kVAr)
6	$\Delta S^{F}_{ij,t}$	Addition capacity of Feeder (MVA)
7	$P^{PV}_{i,s,t,h}$	Active output power of PV (kW)
8	$U_{i,s,t,h}$	Voltage for bus (pu)
9	$\delta_{i,s,t,h}$	Voltage angle at bus (pu)
10	$\alpha_{ij,t}$	Binary variable on feeder upgrade decision (1/0)
11	$\gamma_{i,t}$	Binary variable on feeder upgrade decision (1/0)

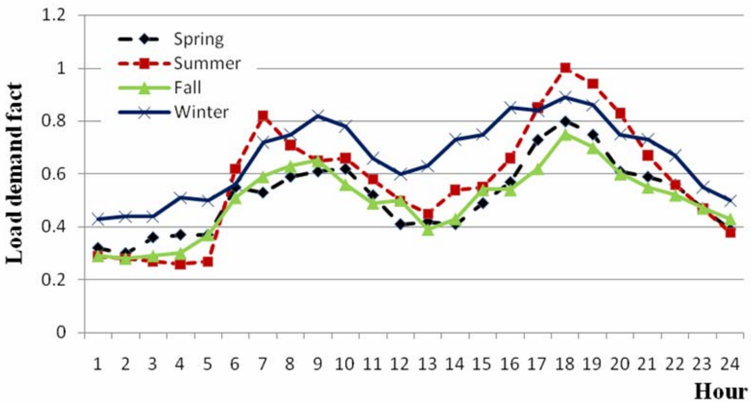

Figure 2. The typical characteristics of load demand for four seasons.

- The constructing cost of 110kV substation including fixed costs and variable costs is 0.2M$ and 0.05M$/MVA, respectively [8]. Similarly, the upgrading costs of 22kV feeders consist of 0.15M$/km and 0.001M$/MVA.km. The assumption life of feeder is 20 year.
- The PV sources are used in this research with the corresponding capital costs to be 3.0M$/MW.
- The average operation and management (O&M) costs is 5 $/kWh and the life of PV is 30 years.
- The energy prices purchasing from electricity markets through substations are shown in Figure 3.
- The PV are manufactured in compact modules occupying small spaces and time to install is short. Hence, the installing areas are not limited and PV can be selected to install at all of load locations. Similarly, areas for upgrading of substation transformers and feeders are not limited.
- The constraints of load nodes voltage limited allow change from 0.9pu to 1.1pu, and it should be 1.05pu at substation node.
- The decided variables in the model are continuous in order to reduce the complexity of the model. Hence, they should be rounded to match real equipments.

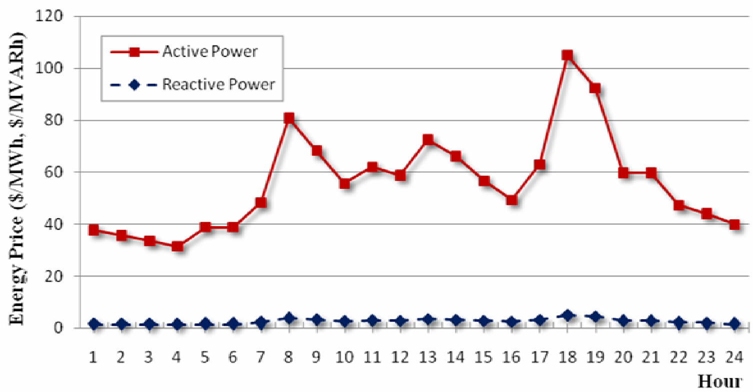

Figure 3. Energy prices purchasing from electricity market.

3.3 The output power characteristics of PV

The power output of PV depends on the intensity of solar radiation and its performance. The power factor of PV calculated basing on the given solar radiation intensity is presented as Figure 4. In contrast, gas turbine does not depend on the nature of the primary energy source so its output power can be constant.

4. Analysis results and discussions

The feasibility of the proposed model and the efficiency of PV are investigated in two cases. Case A is calculated when PV is not considered. While case B integrates PV in the researching model to plan the DS.
The calculation results showed that both cases are upgraded the substation with 10MVA capacity. However, case A is just upgraded at the first year and the investment to upgrade substation in case B is deferred to 3rd year because of the load demand increasing in the future is provided by PV. Similarly, in the case A, 3 feeders need be upgraded in the time from 2nd year to 5th year as represented in Table 4. The

feeders 2-3 and 1-5 in case B are not upgraded during the planning period while only feeder 1-2 is invested to upgrade at 5th year with 70mm^2 section.

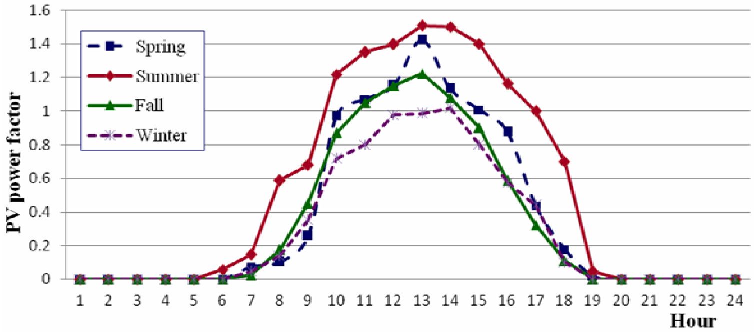

Figure 4. The output power characteristics of PV.

Table 4. Feeders upgrading decisions.

Feeder	Feeder section upgrading in eyear t (mm^2)									
	1	2	3	4	5	1	2	3	4	5
	Case A					Case B				
1-2		70								70
2-3					70					
3-4										
1-5				50						
5-6										
2-7										

Table 5 presents the optimal investment decisions of proposed planning model for PV. The total of investment capacity during planning time is 3.0MW equivalent to 33.9 percent of load demands at base year. The PV are invested and selected that location of these sources are far from substation. Therefore, high economic and technical efficiencies are gained.

Table 5. PV investment decided.

Bus	PV capacity invested in year t (MW)				
	1	2	3	4	5
2					
3			1.0		
4		1.0			
5					
6				1.0	
7					

Economic indicators are compared between case B and case A as shown in Table 6. The case B holds a better economic indicator. Costs for the investment of PV and feeders, substations upgrading are more expensive than those in case A about 4.58M$ due to a very high cost of PV investment. However, O&M and electrical energy expenses that calculated at the base year have been decreased about 0.43M$ because of very low O&M expenses of PV. Therefore, total life cycle cost of case B is lower than these of case A by 0.33M$, equal to 2.22%.

The technical indicators of DS are also improved when PV is integrated on DS planning. The electrical energy loss always reduces during planning period as represented in Figure 5. At just 1st planning years the electrical energy loss is reduced 0.74%, the corresponding 322.92MWh. This value decreases in 4th planning years and it is only 0.25% because the feeders upgraded of case A decrease the resistors of DS. The total of electric energy purchased from markets is also decreased 70,700.0MWh corresponding to 18,382.0tons CO_2 emission of traditional sources [8], which contributes to the decrease of environmental pollutions.

Table 6. Economic indicators comparison.

No	Cost	Case A	Case B	Comparison B and A	Note
1	Total life cycle cost (M$)	14.84	14.51	-0.33	Total life cycle cots is reduced -2.22%
2	Feeder and Substation upgrading cost (M$)	3.52	1.32	-2.2	
3	O&M and Electrical energy cost (M$)	14.32	13.89	-0.43	
4	Investment PV cost (M$)	0	6.78	6.78	

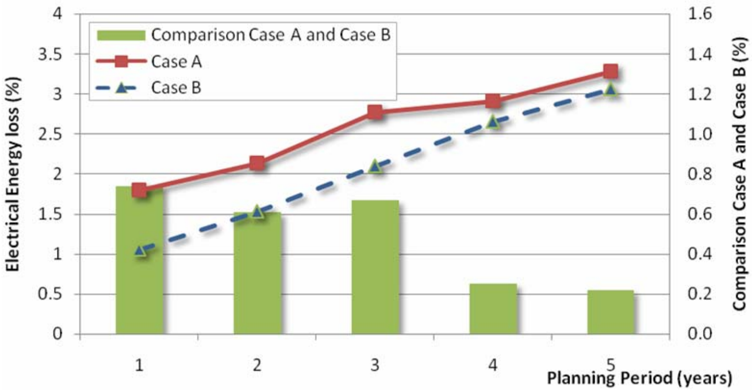

Figure 5. Comparison electrical energy loss between case B and case A.

The transmission capacity on the feeders in case B is lower than in case A due to supported by PV that installed at load nodes. Therefore, the voltage loss of the system reduces and voltage profiles at the all bus are improved during the calculation time. In particular, the load node having the biggest support is 4-bus as shown on Figure 6. This bus voltage profile increased 1.3% at 18th hour in 1st planning year. The 2nd year selected to upgrade feeder 1-2 so the difference of voltage profiles in 2 cases are dropped and then they increase at next year depending on the rise of load demand.

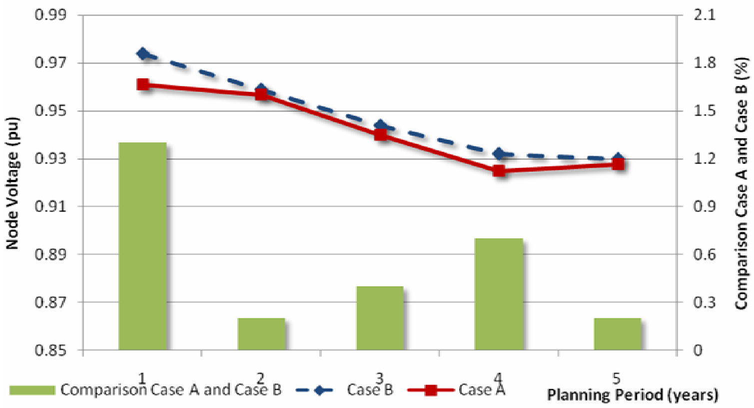

Figure 6. Comparison voltage of 4-bus between case B and case A.

5. Conclusions

Recently, the DS planning has been changed significantly by the impacts of PV and environmental policies. The effect of DS is improved by PV as the enhancement of flexibility and reliability, bus voltage improvement, reduction of transmission cost and power loss as well as the reduction of environmental pollutions. However, the investment cost of PV is usually expensive and power of these sources that used renewable energy has natural variability according to the primary energy so the planning and operation calculation of DS will be more difficult. Therefore, this study proposed a new two-stage optimized model that is integrated PV in DS planning problem. In this model, the equipment sizing and timeframe required for upgrading equipment of DS well as selection technologies and power variable constraints of PV can be determined. The objective function is minimizing total life cycle cost of the investment project. The calculated results showed that the proposed model is suitable in DS planning calculation and the planning together with using PV provided better economics and technical indicators. The total life cycle cost of planning project that integrated PV always reduces. The effects of PV on DS are either on loss reduction or feeders and substations capacity deferment. The power and electrical energy losses also decrease, and furthermore the voltage profiles of nodes are always improved

Appendix

Appendix A. Data of feeder parameters.

No	Bus i - Bus j	F_{ij} (mm^2)	$S_{max.ij}$ (MVA)	L_{ij} (km)	Rf_{ij} (Ω)	Xf_{ij} (Ω)
1	1-2	50	8	2.3	1.362	0.961
2	2-3	50	8	2.2	1.302	0.920
3	3-4	35	6.67	3.3	2.551	1.416
4	1-5	35	6.67	3.5	2.706	1.502
5	5-6	35	6.67	1.7	1.314	0.729
6	2-7	35	6.67	1.2	0.928	0.515

* where: S_{max} - Thermal limit capacity for feeder.

Appendix B. Data of loads.

No	Bus	PD_0 (kW)	QD_0 (kVAr)	No	Bus	PD_0 (kW)	QD_0 (kVAr)
1	1	-	-	5	5	1284.0	1047.6
2	2	651.6	429.6	6	6	2196.0	1929.6
3	3	1950.0	1580.4	7	7	776.4	513.6
4	4	1980.0	1808.4		*Total*	*6465*	*5091*

* where: PD_0, QD_0 - active and reactive power demand at bus in base year of planning period.

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V. V. Thang received the B.Sc. and M.Sc. degrees in department of Electric Power Systems from Thai Nguyen University of Technology (TNUT), Vietnam, in 2001 and 2007, respectively. He received the Ph.D. degree at the Hanoi University of Science and Technology (HUST) in 2015. He is currently a lecturer with the department of Electric Power System, TNUT. His area of research is distributed generation performance and distribution systems planning in deregulated electricity markets