PROPOSING A DISTRIBUTED GENERATION CURTAILMENT OPTIMIZATION MODEL TO MINIMIZE TOTAL POWER LOSSES OF DISTRIBUTION NETWORK

Le Hong Lam[1]*, Phan Minh Nhat[1], Phan Quang An[2,3]

[1]The University of Danang - University of Science and Technology
[2]Ho Chi Minh City University of Technology (HCMUT)
[3]Vietnam National University, Ho Chi Minh City

*Corresponding author: lhlam@dut.udn.vn

(Received: April 20, 2022; Accepted: August 8, 2022)

Abstract - In recent years, Distributed Generation has grown explosively, especially solar power, and the impact of the COVID-19 which has lowed the load, caused the unbalance between electricity supply and demand. In order to solve this problem, the Ministry of Industry and Trade has taken measures to direct Vietnam Electricity to manually reduce this energy source. At present, the member Electricity companies only curtail equally for all investors, this curtailment model is not optimal in terms of power losses. In this study, an optimization model is developed to help power companies obtain an optimal curtailment result in terms of minimizing the power losses on the distributed grid when needed. The proposed model is validated with the real data provided by Thue Thien Hue Power company and commercial software.

Key words - Distributed generation; power losses; distributed network; AC-OPF; PV curtailment

1. Introduction

Power losses are important economic and technical indicators reflecting the effectiveness of the planning, design, production and operation of the power grid. The distribution grid is the end of the process of producing, transmitting and distributing electricity. Where there are a large number of devices, wide range and low voltage, leading to large losses. Therefore, currently, the Electricities are applying many measures to reduce power losses in the distribution grid such as: increasing the conductor's cross-section, regulating the capacity of distribution substations, using high-performance transformers and especially using distributed generation (DG) at the place of electricity consumption.

Since 2017, with policies issued on solar power purchase mechanisms [1-3], in just a short time, solar power projects have been in operation massively, especially in areas of great potential such as the Central and Southern of Vietnam. In addition, in recent years, the Covid epidemic has caused the electricity consumption to drop sharply across the country. These two reasons have led to the imbalance of supply and demand solar power generates a lot while there is no load to consume all. Papers [4-5] have shown that when the DG excess a lot, it increases losses of the grid. This causes overload, instability and unsafety to the power grid.

The Ministry of Industry and Trade has a solution to request The National Load Dispatch Centre (A0) to calculate and announce the reduction of distributed power generation capacity to ensure grid safety and power system security [6], especially the period from 11:00 to 14:00, when the capacity of solar power is high but also the time of low consumption.

Vietnam Electricity (EVN) will direct the National Load Dispatch Centre (A0) in the process of planning operating methods, charting and mobilizing capacity of power sources that need to be forecasted, and accurately calculate the load of the power system; the load of each region to ensure balance of power generation and consumption, and at the same time, it is necessary to calculate the rotational reserve, quick start-up reserve, and transmission capacity to prevent breakdowns.

In case there is a risk that the generating capacity of the system will exceed the load capacity, EVN directs A0 to immediately implement the reduction of the capacity of renewable energy sources being generated to the grid in accordance with the current provisions of the Electricity Law and circulars, current regulations of the Ministry of Industry and Trade, ensuring the safe and stable operation of the electricity system.

After that, A0 will send a dispatch approved by EVN to the Power company of the North, Central and South, including the time and maximum mobilized capacity according to solar radiation to avoid overloading the electricity grid at each region. After calculating, the Electricity will continue to send dispatches to member Power companies to reduce.

So far, the Electricity has only curtailed equal reduction for all investors and customers. This plan ensures that the requirements for total solar capacity need to be reduced, but not optimal when the criteria of grid operation are not considered such as voltage, power losses. Therefore, this paper proposes an optimal mathematical model that minimizes power losses on the grid when curtailing distributed generation. The mathematical model is developed based on the algorithm of AC power flow, so it ensures the technical elements of the distribution grid.

2. Developing a mathematical model to minimize the power on the distribution grid when reducing distributed generation

The proposed model is developed based on the optimization problem. In particular, the objective function is to minimize the total power loss of the feeder. The technical constraints of the distribution grid are all concerned through the constraints of the problem. The results of the paper must ensure that the total capacity needs to be curtailed and not exceed the installed capacity of the customer, while ensuring that this is the most optimal result in terms of losses of the distribution grid.

2.1. Objective function

$$\min OF = \sum_{t=1}^{24} \sum_{i,j=1}^{n} \Delta P_{ij}^{t} \quad (1)$$

The total power loss of the whole feeder is the total capacity loss on each line. In (1), the objective function aims to minimize total power loss across the feeder in one day.

2.2. Constrains

$$P_{c\,i}^{t} + P_{dg\,i}^{t,max} - P_{cdg\,i}^{t} - P_{d\,i}^{t} - P_{ij}^{t} = 0 \quad (2)$$

Constrain (2) is the equation of balancing the active power flow at node i. In particular, the total active power of the DG and the transformer (only concerned the start of feeder) minus the active power demand equal to the total active power of the branches connected to node i. The total active power of DG is calculated by the installed capacity minus the reduced capacity ($P_{dgmax}^{i,t} - P_{cdg}^{i,t}$).

$$Q_{c\,i}^{t} + Q_{dg\,i}^{t,max} - Q_{cdg\,i}^{t} - Q_{d\,i}^{t} - P_{ij}^{t} = 0 \quad (3)$$

Constrain (3) is the equation of balancing the reactive power flow at node i. In particular, the total reactive power of the DG and the transformer (only concerned the start of feeder) minus the reactive power demand equal to the total reactive power of the branches connected to node i. The total reactive power of DG is calculated by the installed capacity minus the curtailed capacity ($Q_{dgmax}^{i,t} - Q_{cdg}^{i,t}$).

$$V_i^{t,min} \le V_i^t \le V_i^{t,max} \quad (4)$$

Constrain (4) is the voltage limit at per node. V_i^t is lower than $V_i^{t,max}$ and higher than $V_i^{t,min}$. In Vietnam generation system, the voltage at the connection nodes is not allowed to exceed 1.05 pu and is not allowed to drop below 0.95 pu.

$$\theta_i^{t,min} \le \theta_i^t \le \theta_i^{t,max} \quad (5)$$

Constrain (5) is the voltage phase angle limit at each node. Phase angle θ_i^t is lower than $\theta_i^{t,max}$ and higher than $\theta_i^{t,min}$.

$$P_{c\,i}^{t,min} \le P_{c\,i}^{t} \le P_{c\,i}^{t,max} \quad (6)$$

Constraint (6) is the active power limit at the connection point of the generator (or distribution network transformer). Each transformer has a different transmission limit so active power transmitted from the transformer is not allowed to exceed this limit.

$$Q_{c\,i}^{t,min} \le Q_{c\,i}^{t} \le Q_{c\,i}^{t,max} \quad (7)$$

Similar to constraints (6) and (7) is the reactive power limit at the connection point of the generator (or distribution network transformer). Each transformer has a different transmission limit so reactive power transmitted from the transformer is not allowed to exceed this limit.

$$-I_{ij}^{t,max} \le I_{ij}^{t} \le I_{ij}^{t,max} \quad (8)$$

Constrain (8) is the limit of the current transmitted between nodes I and j at the time of t. The current flowing in the conductor I_{ij}^t is not allowed to be greater than the maximum designed current for the line $I_{ij}^{t,max}$.

$$P_{cdg\,i}^{t} \le A\ x\ P_{dg\,i}^{t,max} \quad (9)$$

Constrain (9) is for curtailed active power of DG connected to node I, at the time of t. To be fair to all investors, the reduced capacity $P_{cdg\,i}^t$ is not allowed to exceed A of the maximum generating active power of DG at that time $P_{dg\,i}^{t,max}$.

$$Q_{cdg\,i}^{t} \le A\ x\ Q_{dg\,i}^{t,max} \quad (10)$$

Constrain (10) is for the curtailed active power of DG connected to node i, at the time of t. To be fair to all investors, the reduced capacity $Q_{cdg\,i}^t$ is not allowed to exceed A of the maximum generating reactive power of DG at that time $Q_{dg\,i}^{t,max}$. A can be changed at will so as not to be too unfair to all investors.

$$\sum_{i=1}^{n} P_{cdg\,i}^{t} - P_{cut}^{t} = 0 \quad (11)$$

Constrain (11) is the equation that constrains total reduced active power of DG at nodes $P_{cdg\,i}^t$ equal to total reduced active power P_{cut}^t which be required by Power company.

$$\sum_{i=1}^{n} Q_{cdg\,i}^{t} - Q_{cut}^{t} = 0 \quad (12)$$

Constrain (11) is the equation that constrains total reduced reactive power of DG at nodes $Q_{cdg\,i}^t$ equal to total reduced reactive power Q_{cut}^t which be required by Power company.

3. Simulation and results

The mathematical model was developed entirely on the version of GAMS for research community [7-8]. The article applies the model proposed in Section 2 for the feeder 472 substation 110kV Phong Dien – Thua Thien Hue Electricity with different cases to clarify the effect of the DG on the loss of the distribution grid, and the efficiency of the proposed mathematical model in reducing DG power to minimize the loss of the power grid. Currently, in Vietnam, the DG only includes the rooftop solar system.

3.1. Feeder 472 Phong Dien

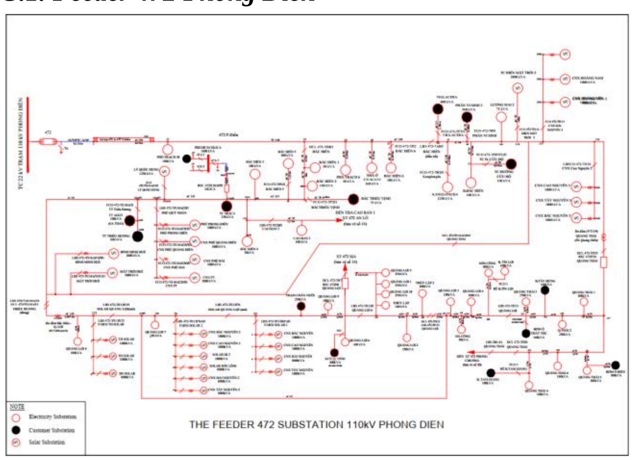

Figure 1. *Diagram of feeder 472 Phong Dien*

The grid diagram of feeder 472 in Figure 1 consists of 101 nodes and is powered by 2x25 MVA transformers. A total of 101 lines and 70 load nodes correspond to 600 customers. In particular, there are 27 nodes with DG installations. Node data, line parameters, load capacity and generating capacity of nodes are collected for each time of a day and provided by Thua Thien Hue Electricity.

The voltage and voltage phase angle at the Point of Interconnection are assumed to be $1\angle 0\ pu$. The limit on node voltage in the distribution grid is from 0.95 pu to 1.05 pu, and the voltage phase angle is from $-\pi/2$ đến $\pi/2$. In this model, the DG is used with only rooftop solar power, so the parameters and variables related to Q of the DG are assumed to be 0.

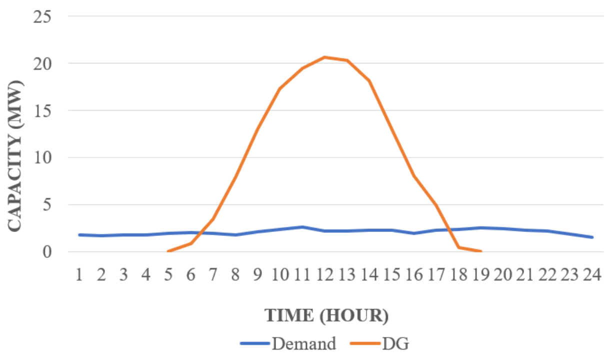

Figure 2. *Load and solar power curve*

The mathematical model is tested with 3 different cases for the purpose of assessing the impact on the power losses of the DG to the grid:

- Case 1: Calculating the power losses of the grid without DG;
- Case 2: Calculating the power losses of the grid with DGs. At this point, DGs generate power as maximum as possible at times of the day, thereby determining the power loss of the grid;
- Case 3: Calculating the curtailment amount of DG power for each node while minimizing the losses.

Assume that the period is from 11:00 to 14:00. The total reduced capacity is (a) 40%, (b) 50%, (c) 60% of total DG capacity, respectively.

First, in order to assess the effect of the DG on the grid, case 1, 2 determine how the power loss on the grid has changed when the DGs join in. Then, to solve the problem posed, the proposed model is run with Case 3 and evaluate the effectiveness of the model.

3.2. Results

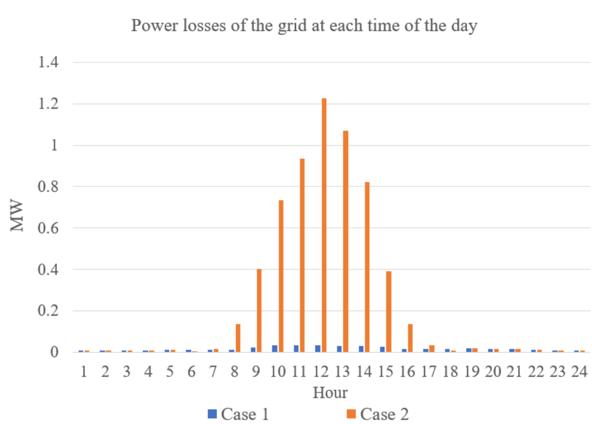

Figure 3. *Power loss chart of the grid in Case 1 and Case 2*

The results of power losses of the grid in Cases 1 and 2 are presented in Figure 3 for 24 hours, while Figure 4 shows only the calculation results from 6 am to 8 am. The blue column is for Case 1 and the red one is for Case 2. In Figure 4, in the early stages from 6 am to 7 am, the power loss of the grid after DGs join in has decreased in comparison to there was no DGs. However, after 7 am, solar radiation increased sharply, rooftop solar generated a large excess power transmitted to the system leading increasing power losses.

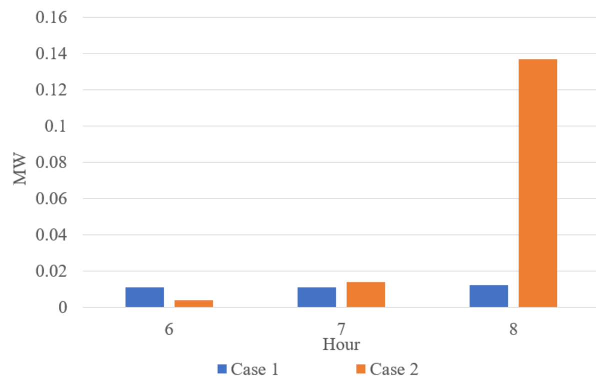

Figure 4. *Power loss chart of the grid in Case 1 and Case 2 at 6 am, 7 am, 8 am*

Apply the proposed mathematical model to determine the curtailment capacity (Section 2) for Case 3 with different total curtailment capacity, obtaining the results as in Table 1, 2, and 3.

Case 3a: Curtailment 40%

Table 1. *DG curtailment power at each node in case of total 40% curtailment (unit: percentage)*

Node \ Hour	11	12	13	14
28/118A/15/14	37.9	34.7	35.6	37.3
28/118A/25/2	31.8	33.8	34.8	36.9
28/118A/25/3	33.0	34.4	35.3	37.3
28/118A/25/4	33.0	34.4	35.3	37.3
28/118A/25/5	33.0	34.4	35.3	37.3
28/118A/32/7A	33.3	34.6	35.5	37.5
28/118A/32/9A	33.4	34.7	35.5	37.5
113/133/1	33	34.5	35.4	37.5
113/133/3	33	34.5	35.4	37.5
113/133/4	33	34.5	35.4	37.5
116/16	33.6	34.4	35.1	37.0
133/1	35.5	36.2	36.8	38.3
133/4	35.5	36.2	36.8	38.3
133/6	35.5	36.2	36.8	38.3
134/1	35.6	36.3	36.9	37.8
134/2	35.6	36.3	36.9	37.8
134/3	35.6	36.3	36.9	37.9
76A/2	48.3	47.0	45.9	43.5
76A/4	48.4	47.1	45.9	43.6
76A/5	48.4	47.1	45.9	43.6
76A/6	48.4	47.1	45.9	43.6

76A/8	48.4	47.1	46.0	43.6
76A/9	48.4	47.1	46.0	43.6
65A/2	51.9	50.2	48.5	44.8
65A/4	51.9	50.2	48.6	44.8
65A/6	51.9	50.3	48.6	44.8
65A/8	51.9	50.3	48.6	44.8

Case 3b: Curtailment 50%

Table 2. *DG curtailment power at each node in case of total 50% curtailment (unit: percentage)*

Node \ Hour	11	12	13	14
28/118A/15/14	50.0	49.1	49.9	50.5
28/118A/25/2	45.9	44.8	45.6	46.3
28/118A/25/3	47.8	47.0	47.8	48.3
28/118A/25/4	47.8	47.0	47.8	48.3
28/118A/25/5	47.8	47.0	47.8	48.3
28/118A/32/7A	47.9	47.2	47.9	48.4
28/118A/32/9A	48.0	47.2	47.9	48.5
113/133/1	47.9	47.1	47.8	48.4
113/133/3	47.9	47.1	47.8	48.4
113/133/4	47.9	47.1	47.8	48.4
116/16	47.8	47.0	46.9	47.2
133/1	48.6	48.2	48.6	48.9
133/4	48.6	48.2	48.6	48.9
133/6	48.6	48.2	48.6	48.9
134/1	48.7	48.3	48.6	49.0
134/2	48.7	48.3	48.6	49.0
134/3	48.7	48.3	48.6	49.0
76A/2	52.7	53.7	52.8	52.1
76A/4	52.7	53.7	52.8	52.2
76A/5	52.7	53.7	52.8	52.2
76A/6	52.7	53.7	52.8	52.1
76A/8	52.7	53.7	52.8	52.1
76A/9	52.7	53.7	52.8	52.1
65A/2	53.7	55.0	53.8	52.8
65A/4	53.7	55.0	53.8	52.8
65A/6	53.7	55.0	53.8	52.7
65A/8	53.7	55.0	53.8	52.7

Case 3b: Curtailment 60%

Table 3. *DG curtailment power at each note in case of total 60% curtailment (unit: percentage)*

Node \ Hour	11	12	13	14
28/118A/15/14	60.7	61.0	61.1	56.6
28/118A/25/2	56.1	56.5	56.0	56.6
28/118A/25/3	58.6	59.2	59.0	57.0
28/118A/25/4	58.6	59.2	59.0	57.0
28/118A/25/5	58.6	59.2	59.0	57.0
28/118A/32/7A	58.7	59.2	59.0	57.1
28/118A/32/9A	58.7	59.2	59.0	57.1
113/133/1	58.7	59.2	59.0	57.1
113/133/3	58.7	59.2	59.0	57.1
113/133/4	58.7	59.2	59.0	57.1
116/16	58.5	59.2	57.9	57.1
133/1	58.9	59.4	59.2	57.6
133/4	58.9	59.4	59.2	57.6
133/6	58.9	59.4	59.2	57.6
134/1	58.9	59.4	59.2	57.7
134/2	58.9	59.4	59.2	57.7
134/3	58.9	59.4	59.2	57.7
76A/2	61.5	60.8	61.1	63.8
76A/4	61.5	60.8	61.1	63.8
76A/5	61.5	60.8	61.1	63.9
76A/6	61.5	60.8	61.1	63.9
76A/8	61.5	60.8	61.1	63.9
76A/9	61.5	60.8	61.1	63.9
65A/2	62.3	61.2	61.7	64.4
65A/4	62.3	61.2	61.7	65.6
65A/6	62.3	61.2	61.7	65.6
65A/8	62.3	61.2	61.7	65.6

The results of Table 1, 2 and 3 show that the farther the DG locates, the more reduction capacity is such as: 65A/2; 65A/4; 65A/6; 65A/8, the percentage reduction of DG at these nodes is more than the DG near the start of the feeder such as 28/118A/25/2; 28/118A/25/3; 28/118A/25/4; 28/118A/25/5. Usually, great reduction at nodes far from the source will reduce the power of transmitted back to the system through a long distance in order to reduce power loss of the grid. But results from Table 1, 2, and 3 show that there isn't any DG reducing percentage at node that reaches 70% of the constraint (9) and (10) due to other constraints such as voltage constrain (4) that cause the DGs near the start of the feeder to also be reduced to ensure voltage constrain at the nodes.

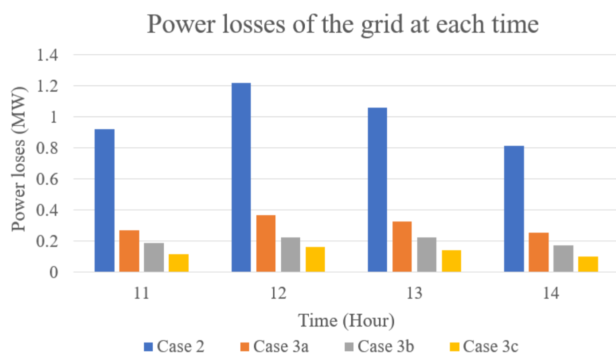

Figure 5. *Chart of power loss on the grid in case 2 and case 3 at times of reduction*

In Figure 5, Case 2 is the total power loss when not curtailing DG, the case 3a is the total power loss when total reduction capacity is 40% of DG capacity, the Case 3b is the total power loss when the reduction capacity is 50% of DG capacity, the Case 3c is the total power loss when the reduction capacity is 60% of DG capacity. The power loss in the cases considering the curtailment of DG is enhanced in comparison to the case without the curtailment of DG, because at this time the power transmitted to the system on the line has been significantly reduced, limiting the overloaded line.

3.3. Compare the proposed model with the current reduction model at the Electricity

Currently, the Electricities reduce equally to all investors (see Section 1). In order to demonstrate the more optimality of the proposed model, the development model will compare with the traditional reduction model of the Electricities. The comparison time ranges from 11:00 to 14:00 when the reduced capacity is 50% of DG capacity.

Table 4. *Power loss comparison table between the proposed model and the traditional model*

Time (hour)	The proposed model	The traditional model
11	0.188	0.195
12	0.255	0.269
13	0.224	0.234
14	0.172	0.177

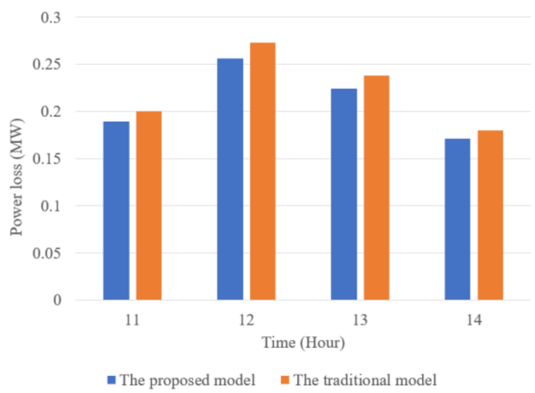

Figure 6. *Comparison chart between the two models in the reduction period*

With the same total reduction capacity, the proposed model results lower power losses than the current reduction model applied at Power companies.

3.4. Validate the proposed model

To validate the accuracy of the proposed model in calculating power flow, the authors compare the results calculated by the model developed on GAMS with the simulation results on the commercial DigSilent software. The time of comparison is 12:00 after reducing 50% of DG capacity. The result calculated by the proposed algorithm is considered as the input value of DGs in DigSilent.

Table 5. *Comparison table of simulation results between GAMS and DigSilent*

	GAMS	DigSilent
Active power entering the transformer (MW)	8.32	8.32
Current entering the transformer (A)	235	235
Power loss of the feeder (MW)	0.26	0.26

The results of the model on GAMS software and the results of the simulation on the DigSilent software are the same, prove that the model developed in this paper is highly accurate.

4. Conclusion

In this study, the paper proposed an optimization model to determine the curtailment capacity of DG at the nodes so that the power losses after the reduction is the smallest, while assessing the effect of the DG on the power grid's power losses in the case before and after the DG joins in, as well as before and after reducing DG. Operators can use the information about the distribution grid to plan for DG regulation to achieve the goal of reducing power losses.

Acknowledgement: We acknowledge the support of time and facilities from Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for this study.

REFERENCES

[1] Thủ tướng Chính phủ Cộng hòa xã hội chủ nghĩa Việt Nam, *Quyết định số 13/2020/QĐ-TTg*, 2020.

[2] Thủ tướng Chính phủ Cộng hòa xã hội chủ nghĩa Việt Nam, *Quyết định số 11/2017/QĐ-TTg*, 2017.

[3] L. H. Lam, H. Van Minh Ky, T. T. Hieu and N. H. Hieu, "Potential and Barriers to the Evolution of Rooftop Solar in Central VietNam", 2021 IEEE *Madrid PowerTech*, 2021, pp. 1-6, doi: 10.1109/PowerTech46648.2021.9494826.

[4] Chiradeja P, Ngaopitakkul A, The impacts of electrical power losses due to distributed generation integration to distribution system, *2013 International Conference on Electrical Machines and Systems (ICEMS), IEEE*, 2013, pp. 1330-1333.

[5] Wang Jian, Gao Houlei, Zou Guibin, Wu Zhigang, Comprehensive evaluation of impacts of distributed generation on voltage and line loss in distribution network, *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), IEEE*, 2015, pp. 2063-2067.

[6] VTC News, *Tiết giảm điện mặt trời là bắt buộc không phân biệt nhà đầu tư*, 2021.

[7] North American Transmission Forum, *Power Flow Modeling Reference Document*, 2013.

[8] Soroudi *Alireza, Power system optimization modeling in GAMS*, Vol. 78, Springer, 2017.

INDEX

Parameters

$P_{c\,i}^{t,max}$ Maximum active power of transformer (MW)
$P_{c\,i}^{t,min}$ Minimum active power of transformer (MW)
$Q_{c\,i}^{t,max}$ Maximum reactive power of transformer (MVAr)
$Q_{c}^{i,t,min}$ Minimum reactive power of transformer (MVAr)
$P_{dg\,i}^{t,max}$ Maximum active power of DG (MW)
$Q_{dg\,i}^{t,max}$ Maximum reactive power of DG (MVAr)
$P_{d\,i}^{t}$ Active power load demand (MW)
$Q_{d\,i}^{t}$ Reactive power load demand (MVAr)
$V_{i}^{t,max}$ Maximum voltage at node *i* (pu)
$V_{i}^{t,min}$ Minimum voltage at node *i* (pu)
$I_{ij}^{t,max}$ Maximum current of line *ij* (kA)
$\theta_{i}^{t,max}$ Maximum voltage phase angle at node *i*
$\theta_{i}^{t,min}$ Minimum voltage phase angle at node *i*
P_{cut}^{t} Total active power of DG that required to be reduced (MW)
Q_{cut}^{t} Total reactive power of DG that required to be reduced (MVAr)

Variables

ΔP_{ij}^{t} Power loss of line *ij* (MW)
$P_{c\,i}^{t}$ Active power from MBA (MW)
$Q_{c\,i}^{t}$ Reactive power from MBA (MVAr)
$P_{cdg\,i}^{t}$ Reduced active power of DG at node *i* (MW)
$Q_{cdg\,i}^{t}$ Reduced reactive power of DG at node *i* (MVAr)
P_{ij}^{t} Active power flow from node *i* to node *j* (MW)
Q_{ij}^{t} Reactive power flow from node *i* to node *j* (MVAr)
V_{i}^{t} Voltage at node *i* (pu)
θ_{i}^{t} Voltage phase angleat node *i*
I_{ij}^{t} Current of line *ij* (kA)