

# A PROPOSED ALGORITHM TO DETERMINE HOSTING CAPACITY OF DISTRIBUTION NETWORK

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**Abstract** - Today, solar energy has great potential and is, therefore, being promoted for use not only in Vietnam but also worldwide. In particular, households with rooftop solar energy can sell excess energy to the power company, which is being noted for strong development. However, the development of rooftop solar will have some negative effects on the distribution grid if the selling capacity from households is too large. PV rooftop is a part of distributed resources. Thus the paper will discuss distributed resources in general. In this paper, an iterative algorithm that determines the maximum number of distributed resources that can penetrate into the grid is developed in the Matlab environment. The proposed model is tested with a simple distribution grid to determine the hosting capacity of the distribution grid.

**Key words** - PV rooftop; distributed generator; hosting capacity; distribution grid; AC power flow

## 1. Introduction

Today, in order to properly implement the policy of industrialization and modernization, the electricity industry must be the driving force in action. The growing industry also means that the demand for electricity is increasing. Along with that, the living standard of the people is increasingly improved, the technology products for their daily life are also diverse. Therefore, the lack of energy will not be avoided. In order not to be passive, we need to introduce new and renewable energies such as wind, solar, ocean wave... into the electricity system.

Vietnam is a country with high solar radiation, so there is huge solar potential [1]. On average, the total solar radiation in Vietnam is about  $5\text{kWh/m}^2/\text{day}$  in the Central and Southern provinces, and about  $4\text{kWh/m}^2/\text{day}$  in the Northern provinces. The number of sunshine hours per year in the North is about 1500-1700 hours, while in the Central and Southern Vietnam, the number is about 2000-2600 hours per year.

Decision 11/2017/QĐ-TTg on the mechanism to encourage the development of solar power projects in Vietnam, issued in April 2017 [2], created a wave of investment in solar power. On the power side, Vietnam Electricity is also investing nearly 20 projects with a total installed capacity of about 2,000 MW in Khanh Hoa, Kon Tum, Ninh Thuan, Binh Thuan and Dong Nai provinces...

In addition, encouraging the development of solar power projects in Vietnam, Decision No. 11/2017/QĐ-TTg states the payment mechanism for selling electricity to EVN from solar investment households [3] and the project for connecting and selling electricity in the distribution network has also been invested to take advantage of the government's incentive mechanism when implemented.

Although this is an interesting option for power users, it is a challenge for power companies as there is a shift from large power plants to small and scattered dispersed sources

in the area assigned to manage. The installation of these Distributed Generators (DGs) can have negative effects on the electrical system. Notably, the development of DGs may bring risks to the grid such as poor operational efficiency or low reliability in energy distribution, or the number of activities of large distributed sources is likely to reach the system limit and as a result of the reduction in power quality and reliability between the utility and the consumer [4], [5].

To solve this problem, two directions are often proposed [6]: (i) Mathematical model to determine the maximum penetration of DGs that can inject to the grid, and (ii) upgrade the distribution grid. The fact that option (ii) will require a large amount of investment and is not appropriate to the actual situation in Vietnam. Therefore, this paper will focus on developing a loop mathematical model to determine the maximum penetration of the DGs in the distribution grid considering some constraints of the network such as voltage, thermal limit of cable, and capacity of transformer. Moreover, the inverter of a Photovoltaic (PV) rooftop system is also considered as an option to increase the amount of penetration when changing the operation modes (leading mode and lagging mode).

The structure of the paper is as follows: Section 2 presents the impact of DGs on the distribution grid and hosting capacity which is an index to evaluate the penetration of DGs in the distribution network. Section 3 develops the algorithm which verified by a simple grid in Section 4.

## 2. Impact of DGs on the distribution grid

When a large amount of energy from a distributed source injects into the distribution grid, the load at each node consumes a fraction of the power generated by the distributed source. Most of the remaining distributed energy will be transferred back to the distribution grid. Most of the distribution networks that are serving in the electrical system are not designed to serve generation at the distribution level. The distribution grid is only designed to distribute power from the source to the load. Although the distribution grid has been designed to have many advantages, it still has many limitations when allowing a large number of DGs to penetrate the grid.

### 2.1. Over voltage

Overvoltage occurs because the direction of the current in the grid is reversed: from the load to the substation.

Figure 1 shows a simple diagram of an AC source and a load  $L$  with a DG.  $U_n$  is the nominal voltage at the slack bus, which will be assumed to be constant and with a power

angle of  $0^\circ$ .  $Z$  represents the impedance of the conductor, including resistance and reactance.  $P_G$  and  $Q_G$  correspond to the active power and reactive power generated by a DG,  $P_L$  and  $Q_L$  correspond to the active power and reactive power of the load at node  $g$ .

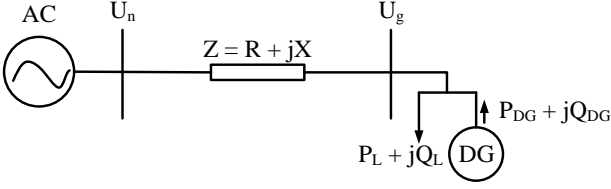


Figure 1. Simple diagram with two nodes and a distributed source.

Typically, the distribution grid is designed to move the power flow from node  $n$  to node  $g$  from source to load. Therefore, the convention of the direction of current and power in Figure 2 is from node  $n$  to node  $g$  and voltage  $U_n$  is known. The voltage  $U_g$  at node  $g$  is calculated as follows:

$$U_n = U_g + \Delta U \quad (1)$$

where  $\Delta U$  is the voltage deviation between node  $n$  and node  $g$ .

Apparent power  $S$  is defined as the total amount of power going from the source to the load to satisfy the required power at node  $g$ . Consumption at  $g$  button:

$$S = (P_G - P_L) + j(Q_G - P_L) \quad (2)$$

Here,  $I$  is the current flowing from node  $g$  to node  $n$ . Ignoring the power loss due to power transmission,  $\Delta U$  can be found using:

$$\Delta U = I \cdot Z = I \cdot (R + jX) \quad (3)$$

$$I = \left( \frac{S}{|U_n|} \right)^* = \frac{P - jQ}{U_n} \quad (4)$$

$$\text{Therefore: } \Delta U = \left( \frac{P - jQ}{U_n} \right) \cdot (R + jX) = \frac{P \cdot R + Q \cdot X}{|U_n|} + j \frac{P \cdot R + Q \cdot X}{|U_n|} = \Delta U_d + j \Delta U_d \quad (5)$$

$\Delta U_d$  and  $\Delta U_q$  describe the axial and transverse components of the voltage. But because the contribution of the transverse component is very small compared to the axial component, it can be ignored. It is as follows:

$$\Delta U = \frac{P \cdot R + Q \cdot X}{|U_n|} \quad (6)$$

In the normal case,  $\Delta U$  is positive because  $P$  and  $Q$  are positive numbers and  $U_g < U_n$ . However, if the power runs from node  $s$  to node  $n$  then  $\Delta U$  is negative, resulting in  $U_g < U_n$ , and if the transmitted power is greater, then  $U_g$  is larger, leading to overvoltage at node  $g$ .

## 2.2. Overheat of Cables and Transformer

Some lines will be overloaded due to its original design just to serve consumption load. When a large amount of DGs is injected into the system, the current transferred back from the load into the grid will be greater than the initial value the cables can withstand.

Specifically, when working normally, before the introduction of DGs:

$$I_1 \geq I_1^{max} \quad (7)$$

That is, the current passing through the conductor must be less than or equal to its allowable limitation.

When a large number of DGs enter the grid,  $I_1$  will increase significantly because of the power transmitted from DGs into the distribution grid of great value because:

$$P_G \gg P_L \quad (8)$$

$$\text{and} \quad I_1 = \frac{P}{U \cdot \cos \phi} \quad (9)$$

$$\text{therefore} \quad I_1 \geq I_1^{max} \quad (10)$$

With a large amount of penetration of DGs,  $P$  will be very large. The power of the selected transformer has nominal values not much different from the consumed load. When DG penetrates, generating a high amount of flow back to the system, this value may exceed the value that the system designer has chosen, resulting in transformer overload.

$$P_L + Q_L \ll P_{DG} + Q_{DG} \quad (11)$$

$$\text{Therefore } S_{DG} \gg S_L \quad (12)$$

Where:  $S_{DG}$ : the power generated by the DG system at each node;  $S_L$ : the power that the load at each node consumes.

## 2.3. Hosting capacity

The hosting capacity of distribution grids often refers to the degree of penetration of DGs in comparison to load that grids can withstand before exceeding one or more performance indices.

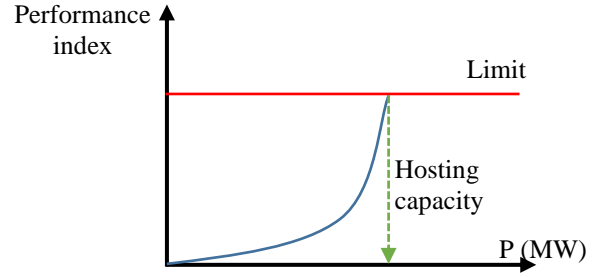


Figure 2. The illustration of hosting capacity

Normally, the level of penetration of DGs in a distribution network is defined as follows: the percentage of total power from the DGs, which is consumed by consumers in the grid, over the total consumption in the grid. However, this study will not focus on increasing the grid capacity for penetration of DGs over years, because the purpose of the study is to analyze the immediate effect of pumping a large amount of DGs into the grid for certain performance indices. Therefore, the penetration of DGs will be defined as the pumping of the energy of the DGs instantly into the distribution network.

Figure 2 presents a simple illustration of the hosting capacity which is used to mention of the maximum number of DGs that can inject to the grid. The value of HC is defined as the penetration of DG respect to the consumption, thus the value of HC is calculated as follows:

$$HC (\%) = \frac{\sum P_{DG}}{\sum P_L} * 100 \quad (12)$$

Where, HC is the value of hosting capacity in percentage.

Here, the hosting capacity of the grid is determined regarding to a performance index with x-axis as the injected power of DGs into the grid and y-axis as a constraint of network. In the case of the high level of penetration of DGs

entering the distribution system, there are three main types for the technical constraints of the network's hosting capacity as below:

- Voltage: expressed as the node voltage relative to the rated value;
- Current: the maximum of power flow on a cable, also called thermal limit of cable;
- Transformer: the maximum power of a transformer.

#### 2.4. Algorithm

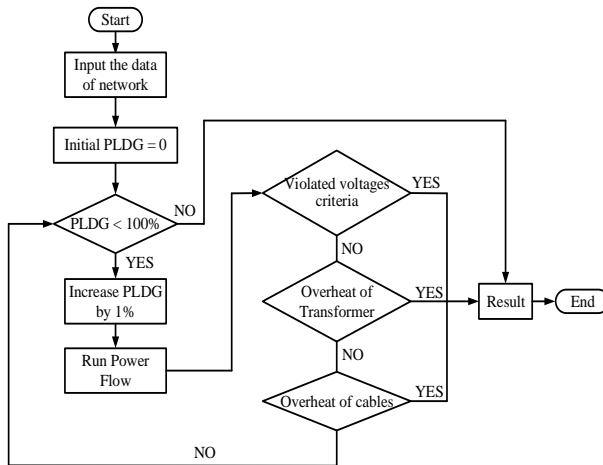


Figure 3. An algorithm to determine hosting capacity

In this paper, a mathematical model to determine the maximum penetration of a DGs into a distribution grid based on an iterative process is proposed as shown in Figure 3. Here, the Penetration value of Distributed Generator is named as PLDG:

$$PLDG = \frac{P_{DG}}{P_{DG}^{max}} * 100\% \quad (13)$$

where:  $P_{DG}^{max}$ : the maximum capacity of a DG, also known as the installed capacity of DG.

The system's technical constraints include: (i) voltage, (ii) transformer and (iii) cable. It should be noted that there are three options used to test the penetration of DGs in a distribution network [7]: (i) forward method in which the DG at the closest node of transformer is increased by 1% then moving to the further node until one constraint of grid is violated, (ii) backward method in which it starts from the farthest node of the grid by an increment of DG of 1% of the installed capacity of DG, and (iii) forward-backward method in which all nodes of the grid have DGs and for each step of loop, DGs will be increased by 1% for all nodes. In this paper, the last method is selected to evaluate the penetration of DGs in distribution network since it consumes least time computation. The steps of the algorithm are described as follows:

- **Step 1:** Enter the initial data into the program. Input data includes system parameters such as node type, transformer parameter, line parameter, load... Note that DG's initial penetration value is 0% and will increase in increments of 1%;
- **Step 2:** Compute power flow;
- **Step 3:** For each penetration value of PV, the algorithm in turn determines the parameters such as node

voltage, power transmitted through transformers, current through cable and then compares them with the limit values (preset). If one of the test values is in conflict, the algorithm will stop and export the data. If all the test values are within the allowed range, the penetration will increase by 1%.

The program will stop when one of the performance indexes are in conflict or the level of penetration of DG of 100%. Based on the value of PLDG, the total certain active power injecting to the network is determined by (13). Eventually, the HC of the network is calculated with (12).

### 3. Test and Result

#### 3.1. Test case

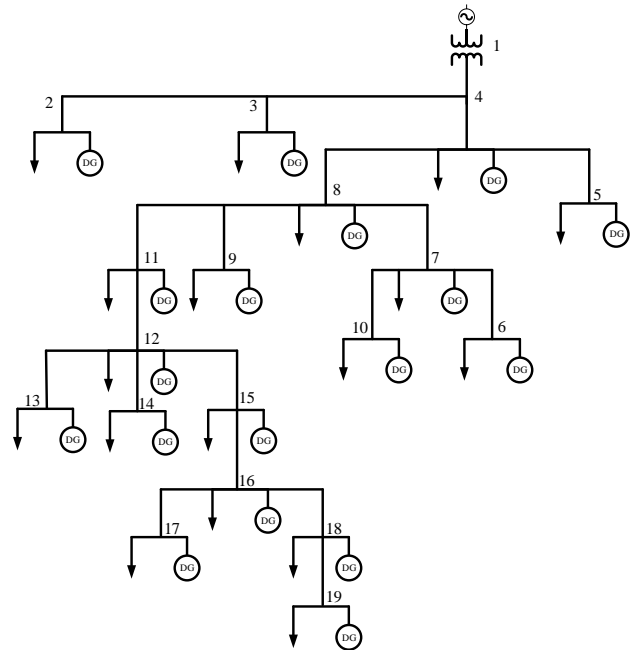


Figure 4. Test case

The mathematical model was implemented in Matlab environment [8] in combination with MAT-POWER [9] to calculate power distribution. A simple distribution grid diagram used to test the proposed algorithm consists of 19 nodes in Figure 4, operating at 11kV, 50Hz. At each node there is a DG and load. The assumption that the load at each node is the same across the distribution system consists of a small load (active power is 0.53MW and reactive power is 0.173MVar) and a DG with a capacity determined based on the penetration level compared to load. The transformer selected was a 10MVA transformer (Mineral-oil-immersed transformer). They receive electrical energy from the transmission network at 110kV and lower the voltage to 11kV, before distributing to a distribution system. Choosing the right cable for the grid depends mainly on two factors: The voltage level (to determine the type of insulation) and the maximum current through the cable (to exploit the cross-sectional area of the conductor). Types of cables and cable parameters are shown in Table 1. It should be noted that the parameter of cables is used based on the data sheet of Elsewedy [10].

**Table 1.** Data of cables

Line	Index	Square (mm <sup>2</sup> )	R( $\Omega$ /km)	X( $\Omega$ /km)	I <sub>max</sub> (A)
1-4	AX2-T101-U70	800	0.0495	0.1708	1468
3-2	AX2-T101-U13	35	1.113	0.2303	164
4-3	AX2-T101-U18	150	0.2645	0.1964	391
4-5	AX2-T101-U13	35	1.113	0.2303	164
4-8	AX2-T101-U70	800	0.0495	0.1708	1468
7-6	AX2-T101-U13	35	1.113	0.2303	164
8-7	AX2-T101-U18	150	0.2645	0.1964	391
7-10	AX2-T101-U13	35	1.113	0.2303	164
8-9	AX2-T101-U18	150	0.2645	0.1964	391
8-11	AX2-T101-U50	500	0.0971	0.1761	802
11-12	AX2-T101-U50	500	0.0971	0.1761	802
12-13	AX2-T101-U13	35	1.113	0.2303	164
12-14	AX2-T101-U13	35	1.113	0.2303	164
12-15	AX2-T101-U18	150	0.2645	0.1964	391
15-16	AX2-T101-U18	150	0.2645	0.1964	391
16-17	AX2-T101-U13	35	1.113	0.2303	164
16-18	AX2-T101-U13	35	1.113	0.2303	164
18-19	AX2-T101-U13	35	1.113	0.2303	164

The model will be tested with two cases for three load Scenarios (SC): ( $SC_1$ ) a low load (50%), ( $SC_2$ ) normal load (100%) and ( $SC_3$ ) high load (120%) compared to transformer capacity. This selection is made to ensure that the proposed method tested in this paper is valid for all load cases. In the case of a 19 nodes test case, the load will be spread evenly across all nodes, in the sense that all nodes consume the same amount of power. In the first case, the power factor of the inverter of PV system is 1 and the values are shown in Table 2, however, it will be changed to 0.97 in the second case to evaluate the impact of operating mode of the inverter on hosting capacity.

### 3.2. Result

According to the data from the above tables, the paper summarizes the penetration of PV compared to the load (hosting capacity) with different load levels and the breach of limits in Table 2.

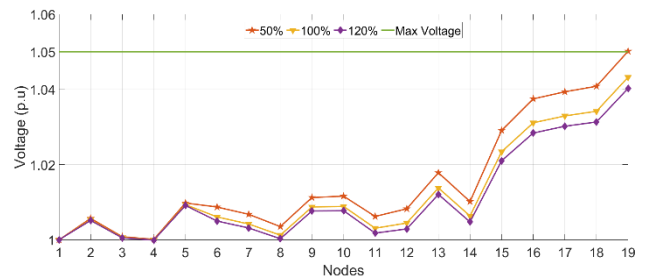
The level of penetration of a DG is the maximum amount of power that DG are allowed to inject into the distribution system without compromising the technical limits. The ratio of penetration to load is the ratio of penetration of scattered power source to load capacity in each case. Meanwhile, the power through a transformer is the excess capacity of DGs when it is supplied to the transmitting from load back to the transformer. The aim of the paper is to identify the correct HC value for the distribution network, thus the transformer is allowed to operate under overloading situation for a short time. The document [11] allows mineral-oil-immersed substation transformers to be loaded at maximum of 200% of their nameplate value. Therefore, 14 MVA (140%) is set as the power limit of the transformer. Notably, the overloading value of the transformer is selected only for a research since it needs another research to be determined correctly for a certain area.

**Table 2.** The result of three scenarios in the first case

SC	Load (MW)	DG (MW)	HC (%)	Transformer (%)	Voltage at node 19 (p.u)	Technical issue
$SC_1$	4.77	20.1	421	99.3	1.05	Voltage
$SC_2$	9.54	25.5	267	99.56	1.043	Transformer
$SC_3$	11.45	27.1	237	99.6	1.04	Transformer

In Table 2, the first column shows three scenarios corresponding to the percentage of rated load capacity. The second column is the active power of load and the third is the active power of DGs. The fourth column presents the hosting capacity which is the level of DG penetration in comparison to load in percentage. The fifth column shows the used capacity of the transformer in percentage and the last column is the voltage at node 19 in p.u. It should be noted that the paper runs AC-power flow, thus the losses of the network is considered.

From Table 2, the hosting capacity decreases since the load increase, but the total DGs which can inject to the network increases. It should be noted that to evaluate the voltage issue, the paper selects the furthest node which is node 19. Here, the voltage at node 19 is violated with the maximum allowable voltage in the first scenario. The first scenario has a voltage violation at node 19 and the voltage profile of all nodes are displayed in Figure 5. The other scenario has an overheat of transformer issue.

**Figure 5.** Voltage profile at nodes in the first case

In the next simulation, the paper will evaluate the impact of the operation mode of generator and inverter of PV system (leading mode and lagging mode) on voltages. Here, DGs from node 2 to node 9 operate at leading mode (power factor is 0.97) and DGs from node 10 to node 19 operates at lagging mode (power factor is -0.97). In another way, DGs from node 2 to node 9 produce reactive power, but DGs from node 10 to node 19 absorbs reactive power.

**Table 3.** The result of three scenarios in the second case

SC	Load (MW)	DG (MW)	HC (%)	Transformer (%)	Voltage at node 19 (p.u)	Technical issue
$SC_1$	4.77	21.1	442	99.98	1.03	Transformer
$SC_2$	9.54	24.5	256	9.59	1.023	Cable (12-15)
$SC_3$	11.45	26.2	229	92.56	1.017	Cable (12-15)

From Table 3, the technical issue of scenario 1 changes from voltage to the transformer, consequently the hosting capacity also increases from 421% in case 1 to 442% in case 2. However, in the other scenarios, the hosting capacity decreases and the technical issue changes from transformer to cable. Therefore, in order to overcome the voltage technical issue, the operating modes of generators

and inverters can be an option and this solution also increases the hosting capacity.

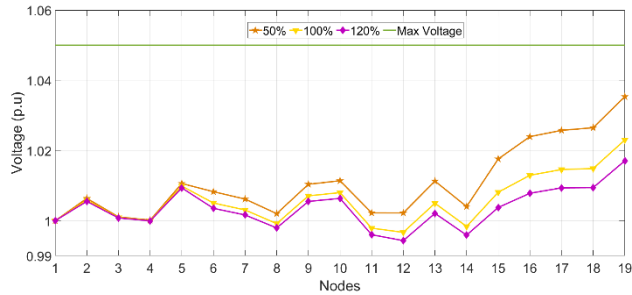


Figure 6. Voltage profile at nodes in the second case

#### 4. Conclusion

The paper successfully implements an iterative algorithm to determine the hosting capacity of a distribution system. The proposed model is tested with a 19 nodes system with two cases and three scenarios of load to verify the robustness of the model. The result shows that the model can provide a value of hosting capacity corresponding to each scenario of load. The hosting capacity is limited by the performance level. Simulation and calculation results can help managers understand the problems that the distribution grid is facing, then take specific measures to improve the hosting capacity of the grid when the penetration of DGs is large. In addition, with the open program, design engineers can apply it to the actual grid for the increasingly sustainable development of the electricity industry.

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