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Developing software to evaluate the ability of distributed energy sources conected to the distribution network

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Abstract

The increasing share of distributed generators (DGs), particularly residential solar photovoltaics systems, are posing new challenges for Distribution Network Operator (DNOs) in the management, operation and planning. They have to adopt more and more advanced tools to evaluate the risk of the grid, plan for infrastructure investment and make informed connection decisions. In conjunction with the power system digital transformation efforts, the study develops a capacity proactive calculation application, which can rapidly assess the impact of new DGs connected to the grid, thereby drawing conclusions about the connection. An application called DERIA helps speed up approvals, interconnections, and expands the penetration of distributed energy resources to support the grid.

***Keywords**: Distributed Generator, Backward/Forward Sweep Load Flow, Hosting Capacity, Distribution Planning.*

Tóm tắt

Tỷ lệ ngày càng tăng của các máy phát điện phân tán (DGs), đặc biệt là các hệ thống điện mặt trời dân dụng, đang đặt ra những thách thức mới cho đơn vị vận hành mạng lưới phân phối (DNOs) trong việc quản lý, vận hành và lập kế hoạch. Họ phải áp dụng ngày càng nhiều công cụ tiên tiến hơn để đánh giá hoạt động của lưới điện, lập kế hoạch đầu tư cơ sở hạ tầng và đưa ra các quyết định kết nối phù hợp. Cùng với nỗ lực chuyển đổi kỹ thuật số trong hệ thống điện, bài nghiên cứu phát triển một ứng dụng có khả năng tính toán chủ động, nhanh chóng đánh giá tác động của các DGs mới muốn kết nối với lưới điện, từ đó đưa ra kết luận về thỏa thuận đấu nối. Phần mềm có tên DERIA sẽ giúp tăng tốc độ phê duyệt các thỏa thuận đấu nối và mở rộng khả năng thâm nhập của các nguồn năng lượng phân tán nhằm hỗ trợ lưới điện.

1. Introduction

Today, there is a global trend toward using clean energy sources to replace traditional kinds of energy. Households choose and install Distributed Energy Resources (DERs), such as solar energy systems, micro-wind turbines, and so on. These offer them with energy independence as well as economic efficiency because surplus energy output can be sold back to power companies. According [1], despite being afflicted by the COVID-19 pandemic, the share of renewables in global electricity generation jumped to nearly 28% in Q1 2020 from 26% in Q1 2019. In Q1 2020 variable renewables - in the form of solar PV and wind power - reached 9% of generation, up from 8% in Q1 2019. In Vietnam, according to statistics of Vietnam Electricity [2], by the end of 2020, the total installed capacity of solar power nationwide is about 19400 MWp (equivalent to 16500 MW), of which rooftop solar power reaches 9300 MWp. In Da Nang City, before September 1, 2019, the rooftop solar PV capacity was only 2.5 MW. But from September 1, 2019 to August 30, 2020, with just one year, 17.7 MW of the new roof solar power system has been put into operation [3]. As the global recovers from the pandemic, solar capacity will continue its upward trajectory. Not only solar power will be strongly invested and developed, but also other distributed energy sources. However, the excessive penetration DERs in the low-voltage grid causes a number of negative effects on the distribution network, such as voltage rise, power quality issues, and protection issues. To overcome the obstacles to DERs integration, it is necessary to assess how many DGs can be integrated into a particular distribution network without causing grid operational criteria to be violated (voltage, thermal, power quality, protection and reliability) and requiring infrastructure upgrades. Because most low-voltage distribution networks are designed to receive power upstream, when DGs transmit power back to the grid system, the technical effects listed above will occur.

In recent years, many methods have been proposed to calculate Hosting Capacity (HC). A more overview of studies on HC for distribution network with DGs that included PV was given in [4]. In general, HC methodology is divided into 3 main methods: Deterministic, Stochastic and Optimization, each approach has its own set of pros and limitations, which are discussed in depth in [5]. These approaches, however, are only useful for estimating overall capacity that can be penetrated or for general planning, and they do not support DNOs in approving a specific RES connected to the grid. This research develops a software called Distributed Energy Resources Interconnection Approval (DERIA), which can help DNOs in making a fast decision to authorize connectivity of a DER by examining its effects on distribution grid

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operating mode. DERIA is designed to do rapid computations, has an intuitive user interface, is simple to use, and can be used anywhere, at any time. The application's purpose is not only for DNOs, but also for customers with limited technical understanding, to create objectivity in the agreement to connect a DER to the grid.
The basic technique for calculating grid values in operation is Load Flow Analysis. Several approaches, including Gauss–Seidel [6], Newton–Raphson [7], and fast-decoupled methods [8], had been developed and employed in the transmission system. In contrast to transmission systems, distribution network conductors have a high R/X ratio [9] and a radial structure with a large number of nodes, branches, distributed generation [10], and complex topology configurations [11], which can be changed for maintenance activities, emergency operations, or network configurations. Transmission grid load flow techniques or Jacobian-based methods, such as Newton–Raphson, Gauss–Seidel, and fast-decoupled methods, failed with such networks due to the high R/X ratios [12]. There have been several efforts to develop power flow algorithms for distribution networks. One of the most commonly utilized methods in scientific publications is the backward/forward sweep method. This method works well with radial distribution network.
Paper [13] presents a direct method of Backward/Forward Sweep Load Flow that is based on the development of two matrices from the network's topological structure: bus injection to bus current (BIBC) and bus current to bus voltage (BCBV), and the solution is obtained by a simple matrix multiplication of BIBC and BCBV. For an electrical system with m branches and n buses, the dimension of the BIBC is "$m.(n-1)$," and the size of BCBV is "$(n-1).m$". In [14], an iterative procedure based on the backward/forward sweep algorithm with the only use of Kirchhoff's formulation is presented to eliminate difficult renumbering of nodes and branches, or any matrix calculation, while remaining adaptable with network topology changes.
Therefore, DERIA uses the core algorithm Backward/Forward Sweep to calculate load flow of radial distribution network in three-phase unbalanced mode, with improvements to integrate DGs at the buses. This method has fast, accurate computation times for radial grids in unbalanced three-phase mode. The decision to choose the Backward/Forward Sweep method was made after a series of tests with very low error results compared to the Newton-Raphson method.
Currently, the research is initially developing software to analyze the connection of PV solar systems to the low-voltage radial distribution network. In future studies, the application will be upgraded to calculate for other energy sources, such as micro-wind turbines, electric heat pumps, micro combined heat and power units;… integrate Supervisory Control And Data Acquisition (SCADA) to get real-time data (grid structure, load, voltage,...) in order to compute more correctly and effectively [14]. The three elements include bus voltage, branch current and transformer loading are the basic modules for calculations in DERIA. In the future, advanced modules such as hosting capacity, short-circuit, unbalanced voltage,… will be investigated.

The remaining part of this paper is organized as follows. In Section 2 illustrates the methodology of Backward/Forward Sweep Load Flow. Section 3 provides a summary of DERIA implementation process. In Section 4, case study and simulation results are shown and discussed. Finally, the main conclusion is summarized in Section 5.

2. Backward/forward sweep load flow

According to these several forms of the low-voltage radial distribution network, there are four types of bus: Sub-terminal bus, Terminal bus, Common bus, and Intermediate bus, as show in Figure 1.

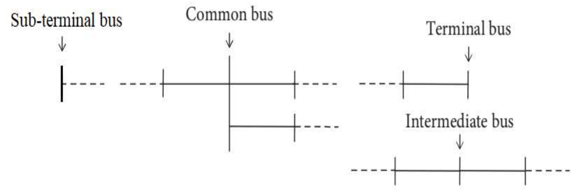

Figure 1: Types of network buses

The backward/forward sweep method is based on three key steps [13]. Starting from the terminal node, considering the electrical characteristics presented in Figure 2 the following three key steps are formulated.

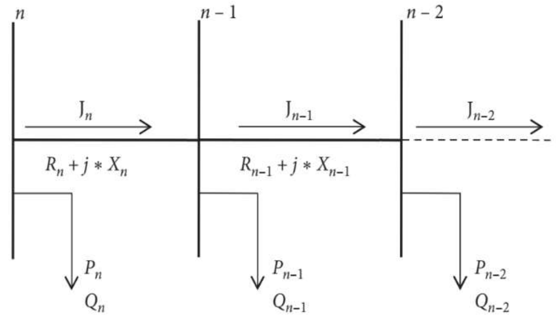

Figure 2: Single line diagram

Step 1 (bus current calculation): the current injection at each bus $n-i$, phase p is calculated using the following equation:

$$I_{n-i}^{p,(k)} = conj\left(\frac{P_{n-i}^{p} + j * Q_{n-i}^{p}}{V_{n-i}^{p,(k)}}\right) \quad (1)$$

$$i = 0,1,\ldots,n-1$$
$$p = 1,2,3$$

where $S_{n-i}^{p} = P_{n-i}^{p} + j * Q_{n-i}^{p}$ is the power injection at bus $n-i$, phase p and $V_{n-i}^{p,(k)}$ is the voltage of bus $n-i$, phase p calculated from iteration k.

Step 2 (backward sweep): starting from the last ordered branch, current J_{n-i}^{p}, in branch from the bus $n-i$ to the bus $n-i-1$, phase p is calculated using the following equation:

$$J_{n-i}^{p,(k)} = -conj\left(\frac{P_{n-i}^{p} + j * Q_{n-i}^{p}}{V_{n-i}^{p,(k)}}\right) + \sum_{r} J_{n-r}^{p,(k)} \quad (2)$$

$$r = 0,1,\ldots,n-1$$
$$p = 1,2,3$$

Where $\sum_r J_{n-r}^{p,(k)}$ is the current in branches emanating from bus $n-i$.

Step 3 (forward sweep): starting from Sub-terminal bus, the bus voltages are updated using the following equation:

$$V_{n-i-1}^{p,(k)} = V_{n-i}^{p,(k)} - Z_{n-i}^{p,(k)} * J_{n-i}^{p,(k)} \quad (3)$$
$$i = 0,1,\dots,n-1$$
$$p = 1,2,3$$

Where $Z_{n-i}^{p,(k)}$ is the series impedance of branch from bus $n-i$ to bus $n-i-1$, phase p.

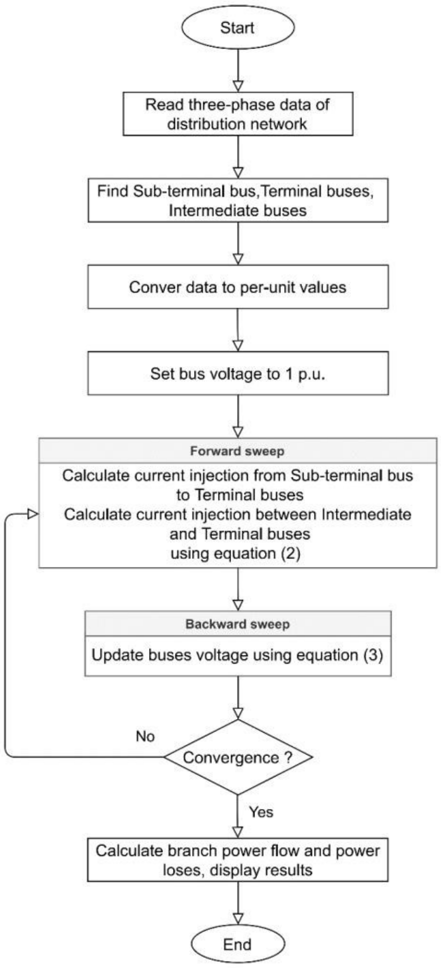

Figure 3: Flow chart of backward/forward sweep load flow

Those three steps are repeated until voltage magnitudes at each bus in the present iteration and the previous iteration is lower than a tolerance limit ε:

$$max\left(\left[V_{n-i}^{p,(k+1)}\right] - \left[V_{n-i}^{p,(k)}\right]\right) \leq \varepsilon \quad (4)$$

If a network had no common buses and no derivation lines outgoing from those common buses, the branch current calculated in the forward sweep will be calculated only by the use of Eqs. (2). The flow chart of method is given in Figure 3.

3. Distributed Energy Resources Interconnection Approval Sofware

Figure 4 provides a flowchart of the DERIA software working process with following steps:

1. Model a distribution network and establish the initial conditions.

The operating conditions of distribution network are regulated by DNOs in [15] as follows:

- Voltage must be below 1.05 p.u. and above 0.95 p.u.
- Conductor currents must be below the conductor thermal limits.
- Transformer loading must be lower than 100% of transformer rated capacity.

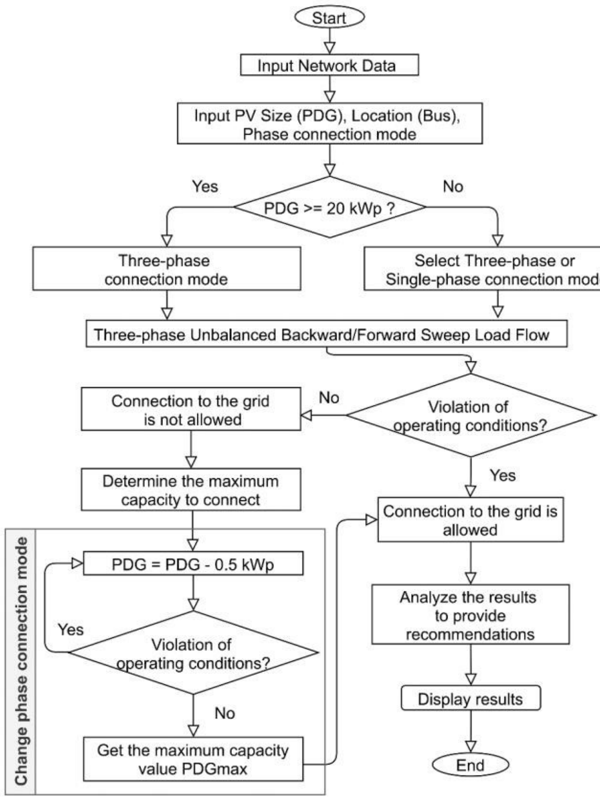

Figure 4: Flow chart of DERIA process

2. Input data including PV size, installation location, phase selected connection (single-phase or three-phase).

According to the circular regulation of Vietnam Ministry of industry and trade [16], PV system with peak capacity of 20kWp or more must be connected to the grid in three-phase mode, lower values can connect single-phase or three-phase.

3. Run three-phase unbalanced backward/forward sweep load flow to ascertain the grid's operational state.

4. If no violation occurs during the connection, show the approval to connect the PV system to the grid.

5. If one of the operating limitations is violated, the PV system's connection to the grid is disabled. Carry out the computation of the maximum power that can be installed at the selected bus by executing 0.5kWp reduction loops until no further violations are found. Changing the phase connection mode (three-phase to single-phase and vice versa, phase A to phase B,...) to obtain the maximum permissible installed capacity value is also performed during the calculation.

6. Analyze the aforementioned results in conjunction to provide recommendations for the operation plan and the ability to accept additional capacity from DER system.

Initially DERIA simply considered adding a PV source to a bus for the sake of users including individual customer and operators. In case of adding N PV sources to N different buses, there are two solutions:

- The first method is for consumers who register first to be given priority in calculating. Of course, the capacity of the early comers is usually greater than the capacity of the late ones. The implementation method is to use DERIA's original algorithm to determine the maximum capacity of each PV source in turn (in the order of customer registration) until the grid's reception capacity reaches 100%.

- The second method is to modify the DERIA model to accommodate multiple sources connected to multiple buses. Methods include: (1) At the same time gradually increase the capacity of N PV sources at N buses until one of the operating constraints is violated. (2) Gradually increase the capacity of one PV source until it reaches the maximum and then move on to the next PV source. For the case of N PV source connect to N buses, there are N factorials for choosing PV order. The end result is the case of obtaining the highest total installed capacity for the N PVs.

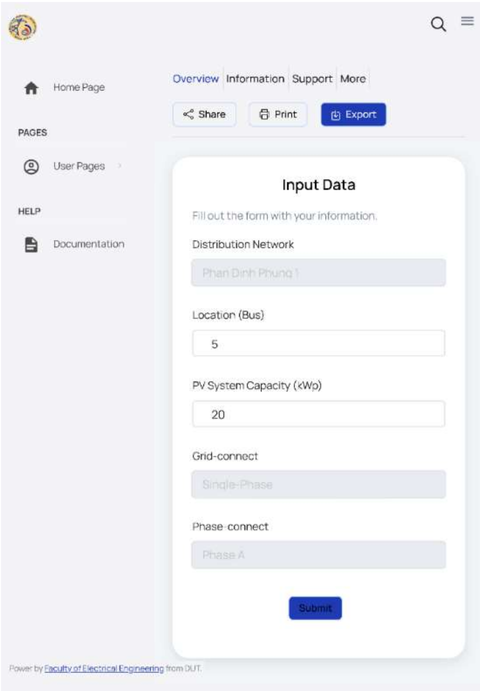

Figure 5: DERIA's input data interface

To be intuitive, convenient and easy to use anywhere, DERIA is designed to be a JavaScript-based website. After entering the input data, the DERIA tool calls the MATLAB program, which calculates the effect on the grid when making the DG connection and transfers the data results to the interface web page, using the REST API method. DNOs can automate the process of updating DERIA data with measured data from the SCADA system, also embedding DERIA in their website system for internal use and increasing information security. Figure 5 depicts the DERIA's input data interface.

4. Simulation results

The study uses a low voltage distribution grid in Da Nang City, operating at 0.4kV and 50Hz. This network includes 21 buses, 145 customers depicted by single line diagram in Figure 6. Conductor cables used in this distribution grid include A(4x240) operated parallel and ABC95 with rated currents of 1180A and 267A respectively. The three-phase load data and available DGs at the buses are shown in Table 1 (see Appendix). The load's power factor is fixed at 0.95 inductive and assuming that PV output power is equal to peak power, cosφ = 1. The transformer with rated capacity of 630kVA, receive electrical energy from the medium voltage network at 22 kV before distributing to a distribution system. Mutual inductance of distribution lines and phases are ignored in low-voltage distribution network. Assume that all phases in the same branch use the similar conductors. Voltage on the low-voltage side of transformer (Sub-terminal bus) is fixed at 1.03 p.u.

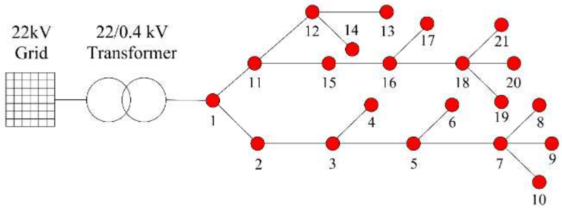

Figure 6: Distribution network test case

A PV system with a capacity of 200kWp is installed at bus 7, three-phase connection mode. The calculation results are shown in Figure 7-9. Figure 7 shows that the connection could not be approved due to voltage violation and causing line overload, according to the results of an impact evaluation of the 200kWp PV system on the distribution grid. Analyzed in Figures 8 and 9, the violation is caused by overvoltage at bus 10 (1.057 p.u.) and over-current at branch number 6 (123.51% load-carrying rate).

Figure 10 presents the results of calculating the maximum installed capacity of the aforementioned system. The highest power available at bus 7 is 79 kWp and satisfy all operating conditions like voltage below 1.05 p.u. and the highest line load is just 77.15%. However, when this capacity is installed, the voltage here will be the highest (1.049 p.u.), making operation problematic. DNOs can set the constraints of the algorithm to obtain the maximum power that meets a desired voltage value. Installing a capacity of 79kWp will prevent bus 7 and perhaps those nearby buses from accepting future connections of additional DER.

5. Conclusion

The paper successfully develops a useful and essential piece of software to calculate the impact of DGs on the distribution network, thereby giving approval for the connection and future operating plans. DERIA software can directly support customers, thereby creating transparency in connection agreements. The results have shown the flexible calculation capabilities of this software. Its results can help DNOs 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 to the actual grid for the increasingly sustainable development of the electricity industry.

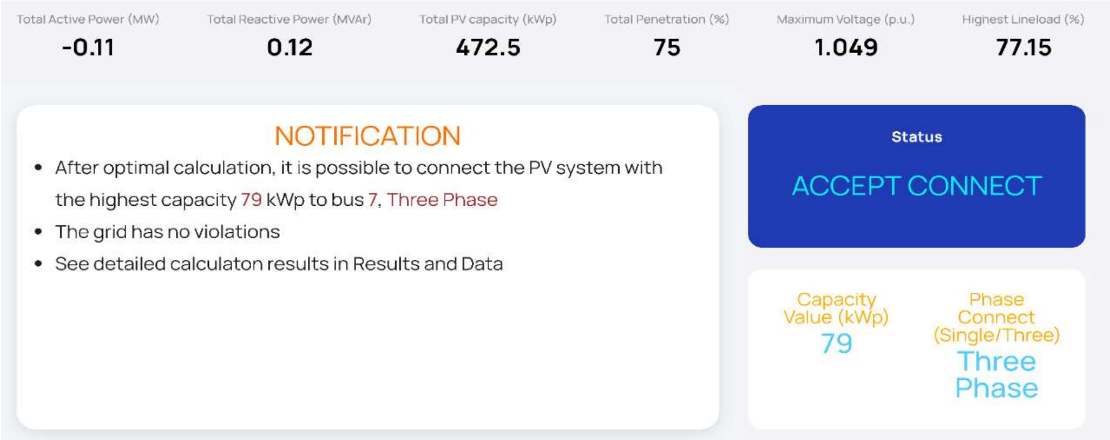

Figure 7: Result of approval connection

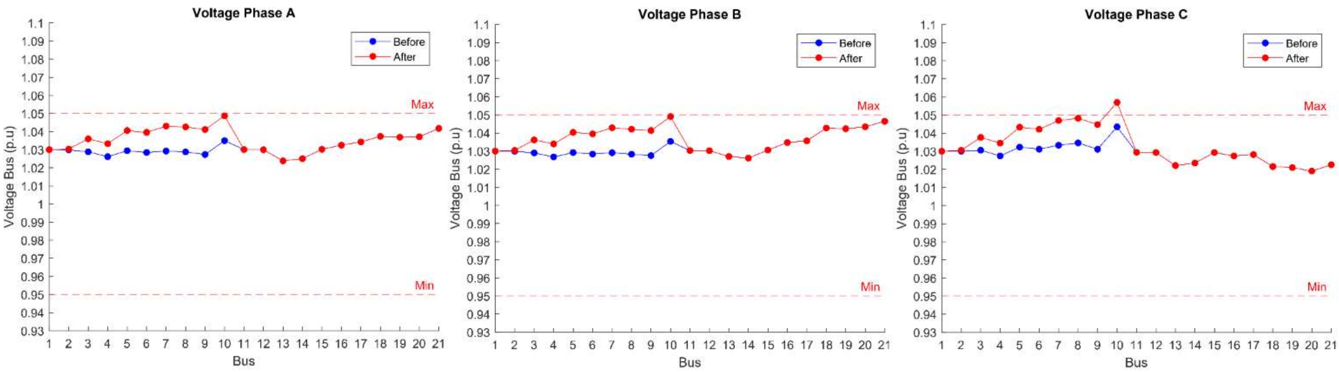

Figure 8: Result of bus voltage

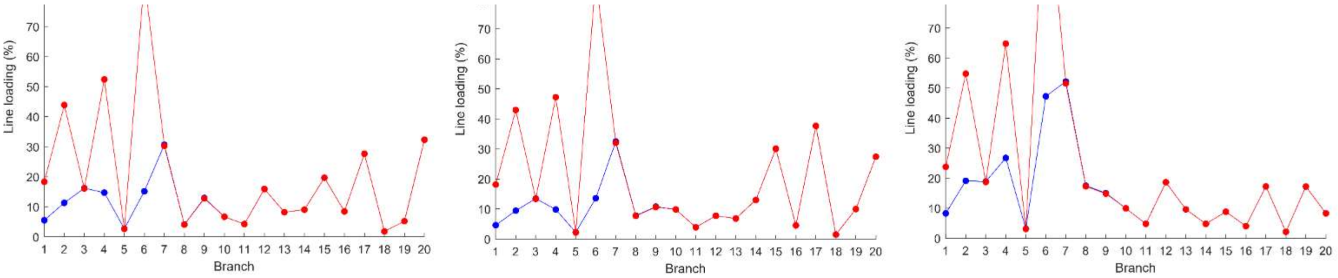

Figure 9: Result of current branch

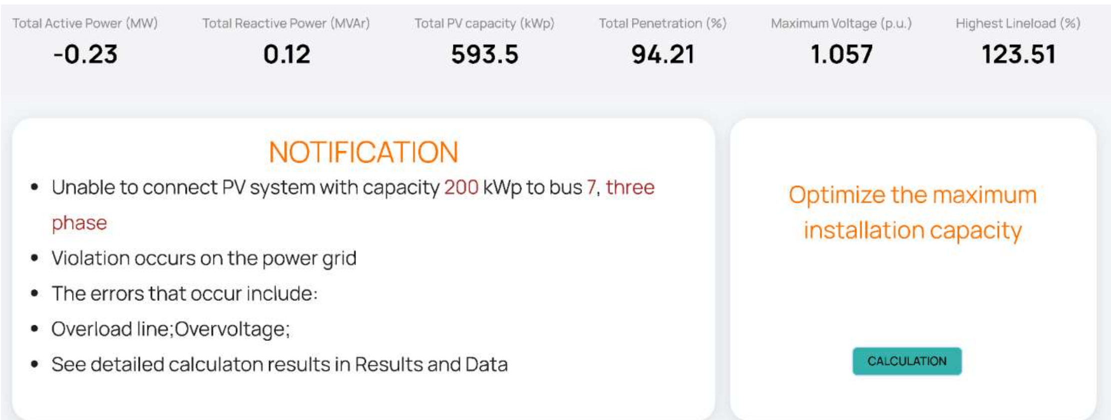

Figure 10: Result of calculating the maximum capacity PV system

Appendix

Table 1. Data of three phase load and DGs

Bus	PLa (kW)	PLb (kW)	PLc (kW)	PDGa (kWp)	PDGb (kWp)	PDGc (kWp)
1	0.07	0.06	0.08	0	6	0
2	6.49	5.41	7.57	0	0	3
3	2.88	2.40	3.36	0	5	0
4	12.77	10.65	14.90	0	0	0
5	2.53	2.86	3.87	20	10	10
6	4.27	3.56	4.98	0	0	0
7	7.55	6.29	8.81	0	0	0
8	7.40	6.17	8.64	5	0	23
9	10.22	8.52	11.93	0	0	0
10	9.50	7.92	11.09	35	35	55
11	1.43	1.19	1.67	0	0	0
12	2.76	2.30	3.22	8	0	10
13	12.54	10.45	14.63	0	5	0
14	6.48	5.40	7.56	0	0	0
15	2.76	2.30	3.22	3	0	0
16	4.62	3.85	5.39	0	15	1
17	2.87	2.39	3.35	17	10	10
18	5.31	4.43	6.20	0	6	3
19	1.44	1.20	1.68	0	0	0
20	12.34	10.28	14.39	14	18	1
21	2.76	2.30	3.22	30	25.5	10
total	119.1	99.9	139.8	132	135.5	126

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