Interconnection Study of a 3 MWp Solar Farm on 20 kV Distribution System Considering Power Flow and Short Circuit

Nadyanti Larasati[1], Amien Rahardjo[2], Hanindito Titah Prameswara[3], and Faiz Husnayain[4*]

[1, 2,3,4] Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia
Corresponding Email: [*] faiz.h@ui.ac.id

Abstract – **Currently, renewable energy is under review so that its use can be more widespread in the future. One of the renewable energy sources that are commonly used is solar energy through solar cell technology that can convert solar energy into electrical energy and then becomes one of the components that makes up the solar power plant. The use of the solar power plant can be interconnected with distribution networks in electric power systems, both medium-voltage networks and low voltage networks. In this study, a 3 MWp capacity of solar power plant was conducted with the medium-voltage network system of X City. This interconnection study consisted of power flow and short circuit studies using ETAP 12.6.0 software. The results of the power flow study show the voltage level of each bus has increased by 0.293%-0.926% after interconnection with the solar power plant system, with a value that still matches the SPLN 1:1978 standard of 90% to 105%. Besides, the results of short circuit study show the value of the three-phase short circuit fault current experienced a change in value that is not too significant, with an increase of 1-37 A and a decrease of 1-5 A, with a value that is still according to the protection component rating standard of 25 kA.**

Key words: Load flow, interconnection, short circuit fault, solar power plant.

I. INTRODUCTION

Nowadays people's need for electricity is increasing. To fulfill people's demand for electricity, a reliable electric power system is needed. Electricity generation is an important component that can support electricity needs for consumers. In Indonesia itself there are various sources of energy that can be converted into electrical energy. However, the government is currently focused on renewable energy sources.

One of the renewable energy sources that is commonly used in Indonesia is solar energy. Solar energy is currently one of the most growing and reliable energy source all over the world as this type of energy is the most abundant, clean, and eco-friendly of all the renewable energy resources [1]. Solar energy can be utilized through the solar photovoltaic.

Solar electricity of photovoltaic (PV) technology converts sunlight directly into electricity [2]. Solar power plant is an electrical generation system by converting photon energy of sunlight into electrical energy. The electrical energy produced by solar cells is in the form of

direct current or DC that can be directly used for DC electrical equipment or to recharge batteries. However, the solar power plant itself needs AC electrical energy output so that it requires an inverter to convert DC to AC.

Installation of the solar power plants in the electricity network that is currently available is expected to improve the voltage profile and help to fulfill the needs of electrical energy in the area where the solar power plants are interconnected, especially with support that has been stated by the government. In this journal, the solar power plant is simulated for interconnection in the X City electrical system. The solar power plant interconnection simulation is supported by a statement in Electric Power Supply Business Plan for 2019-2028 (known as RUPTL) by the PT PLN (Persero).

The impact of 3 MWp solar power plant interconnection with medium-voltage network at X City can be known through load flow analysis and short circuit fault analysis. Load flow analysis is an analysis used to calculate the amount of voltage, current, active power, reactive power, and power factors that are present at various points in an electric power line under normal operating conditions [3]. Short circuit fault is a disturbance in the electric power system that can cause overcurrent which is usually much greater than the rated current of the equipment.

The rural electrification strategy is carried out with the development of the existing distribution network. However, for areas that are still isolated and not possible to develop electricity networks will be generated by power plants that take precedence over local renewable energy [4]. If this simulation can be applied, an increased electrification ratio in the X City region is expected so that it participates in realizing 100% of the national electrification ratio.

This study has several predetermined problem statements. This research was conducted by operating a simulation of power flow analysis and three-phase short circuit faults on ETAP 12.6.0 software. This research is planned on the solar power plant system with a capacity of 3 MWp. Furthermore, the data taken and analyzed from this simulation are the power, voltage, and three-phase short circuit fault current on each bus.

The objective of this research is to obtain results in the form of the interconnection effect between a 3 MWp solar power plant and a 20 kV medium-voltage network in X

City using simulations from ETAP 12.6.0 software.

II. METHODOLOGY

A. *Flow Chart of the Study*

This study aims to analyze the effect of connecting the renewable energy power plant in the form of solar power plant with a capacity of 3 MWp in terms of the power flow and short-circuit fault current to the X City power system.

The first stage carried out for this research is to collect literature studies sourced from physical and electronic books, scientific journals, the internet, and the outcome of consultations with the supervisor. Next is to look for the data requirements needed for the simulation. The simulation begins by rearranging X City's single line diagram (SLD) on the ETAP 12.6.0 software worksheet. Then, the next step is to select the solar power plant specification that wants to be used and add it to the X City SLD that has been created.

When the solar power plant is installed, simulation on ETAP 12.6.0 software can be operated. In this research, simulation of power flow analysis and short circuit fault analysis are operated. The results of the data obtained from the simulation are analyzed so that later the effect of the solar power plant installation is known in accordance with the objectives of this study. The following is a testing process flow chart in this study as shown in **Figure 1.**
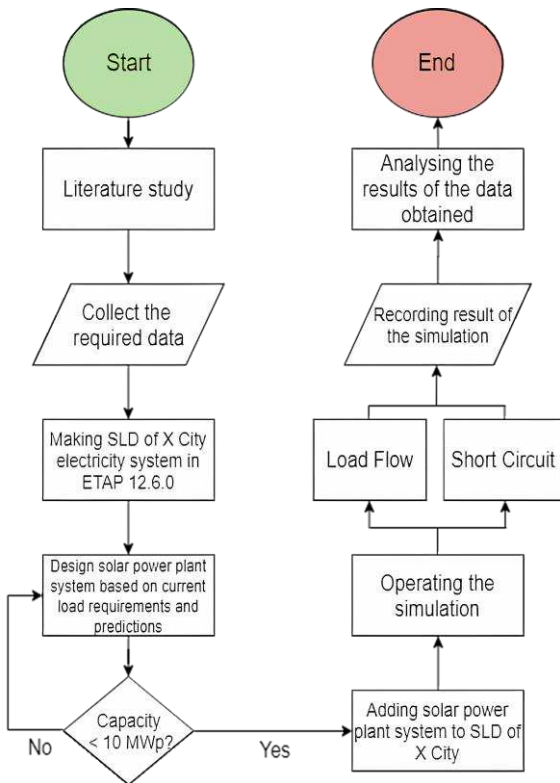
Figure 1. Flow Chart of The Study

B. *Simulation Using ETAP 12.6.0*

In this study, the experimental instrument used was ETAP (Electrical Transient and Analysis Program) software version 12.6.0. In this software, simulation of electricity system can be done along with various analyzis of the system.

The simulation can be run by first assembling a single line diagram and determining the representative specifications of each component. After that, the simulation can be operated based on the desired analysis.

The simulation of power flow and short circuit fault are each conducted with two scenarios, including:
1. Scenario 1, consists of power flow analysis of two sub-scenarios:
   a. Scenario 1A, namely condition of the power flow before 3 MWp solar power plant is interconnected to the X City 20 kV medium-voltage network system.
   b. Scenario 1B, namely condition of the power flow after 3 MWp solar power plant is interconnected to the X City 20 kV medium-voltage network system.
2. Scenario 2, consists of short circuit fault analysis of two sub-scenarios:
   a. Scenario 2A, namely condition of the short circuit fault before 3 MWp solar power plant is interconnected to the X City 20 kV medium-voltage network system.
   b. Scenario 2B, namely condition of the short circuit fault after 3 MWp solar power plant is interconnected to the X City 20 kV medium-voltage network system.

C. *X City Profile*

1) *Electricity Condition of X City*

This study will be implemented in the X City electricity network which operates on a medium-voltage network, precisely at a voltage level of 20 kV. PT PLN (Persero) itself fulfills the load requirements in X City through a diesel power plant located in the Bus 3 and Bus 4 power stations. This system consists of 5 generators. Apart from PLN, the fulfillment of load needs in X City is also fulfilled by Excess Power in the form of rent or IPP (Independent Power Producer).

The 20 kV medium-voltage network system in X City uses a medium voltage overhead line with AAAC (All-Aluminium Alloy Conductor) type with a cross-section area of $3x95$ mm^2. This type of conductor has a current carrying capacity worth 250 A [5]. In this study, the electrical system will be represented by a single line diagram simulated in ETAP 12.6.0 software (as shown in **Figure 2**). To operate the simulations required completeness of data in the form of specifications of each component.
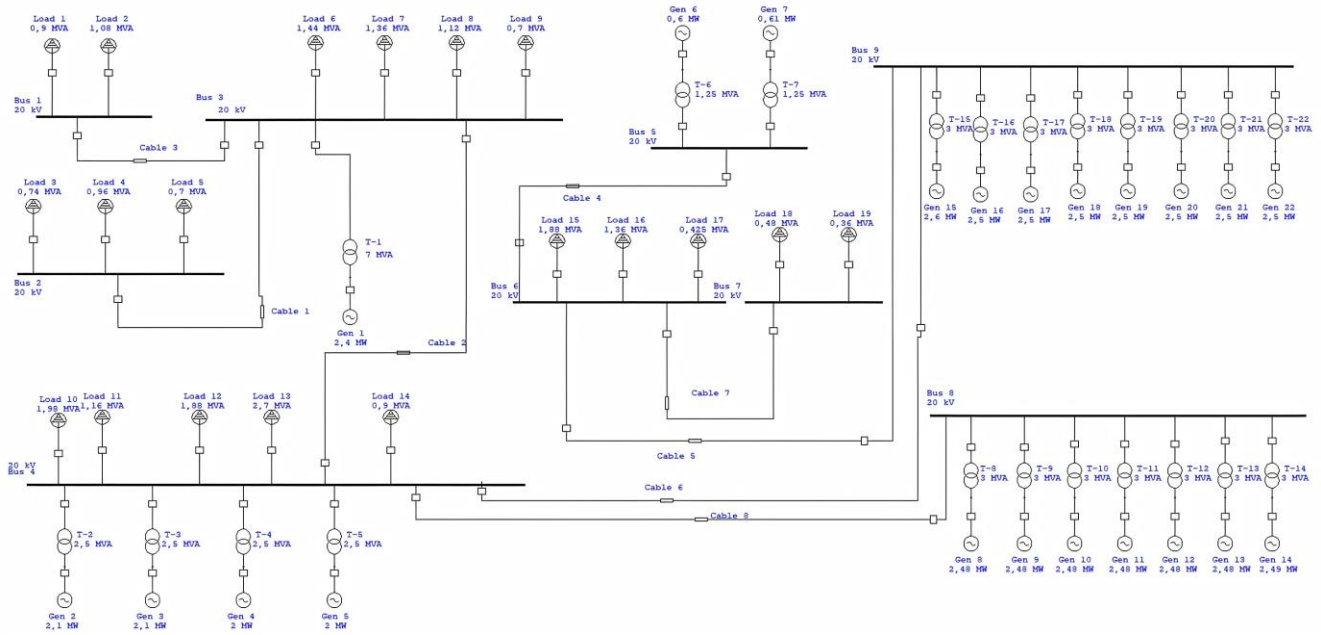
Figure 2. Single Line Diagram of X City

2) Generator Specification

X City electricity system consists of 22 generator units with varying capacities. The generators supply power to the surrounding loads with varying distances too. Generator specifications available in the X City electricity system can be seen in the following **Table 1**.

Table 1. Generator Specifications of X City Electricity System

Generator Unit	Capacity [MW]	Connected with Bus	Operation Mode
PLN Unit			
Gen 1	2.40	Bus 3	Swing
Gen 2 - 3	2.10	Bus 4	MVAR Control
Gen 4 -5	2.00	Bus 4	MVAR Control
Excess Power			
Gen 6	0.60	Bus 5	Voltage Control
Gen 7	0.61	Bus 5	Voltage Control
Gen 8 - 13	2.48	Bus 8	Voltage Control
Gen 14	2.49	Bus 8	Voltage Control
Gen 15	2.60	Bus 9	Voltage Control
Gen 16 - 22	2.50	Bus 9	Voltage Control

In this simulation, supporting data or parameters related to the specifications of the generator used are needed. One of the parameters is the output voltage level of the generator valued at 6.3 kV and 0.4 kV.

D. The Solar Power Plant Planning

The main objective of the solar power plant interconnection planning with a 20 kV medium-voltage network of X City is to fulfill the load needs in X City. Currently, the X City electricity system supplies electricity to meet the existing loads in X City with a total of 22.13 MVA. In this study, it is assumed that the system has a baseload requirement of 50% of the peak load or 11.07 MW.

The growth rate of electricity demand in the X City region from 2003 to 2020 is assumed to increase by 9.4% per year [6]. That means with the condition of the load requirement of 22.13 MVA and an increase in electricity demand of 9.4%, then in the following year the load requirement will be 24.21 MVA. In other words, the load requirement will increase by 2.08 MVA so the installed solar power plant must be able to help fulfill the load needs.

In addition to the load requirements, the current carrying capacity value in the conductor can also be one of the considerations in determining the capacity of the solar power plant. The type of conductor used in this simulation is BS6622 contained in the ETAP library 12.6.0 with a conductor cross-sectional area of 95 mm² and a frequency of 50 Hz. This refers to the type of conductor that is used in the X City electrical system, the medium voltage overhead line type AAAC (All-Aluminium Alloy Conductor) with a cross-sectional area of 3x95 mm². Based on the provisions of the General Electrical Installation Requirements (known as PUIL) of 2011, this type of conductor has a current carrying capacity value of 250 A [5]. The current carrying capacity of BS6622 conductor based on simulation is 231.93 A. Since the solar power plant system will be interconnected with medium-voltage network of X City (20 kV nominal capacity) with a current carrying capacity value of 231.93

A, solar power plant can be installed with a maximum power of 8.03 MW.

Based on considerations in the form of load requirements and the current carrying capacity value used in the system, it was determined that the solar power plant would be interconnected with the X City electricity system with a power of 3 MWp. This capacity fulfills the main requirements in the interconnection of new renewable energy, which capacity must be under 10 MW. Besides, 3 MWp solar power plant system that is interconnected with 20 kV medium-voltage network of X City will produce a current flowing at 86.6 A. The current value is still below the system's current carrying capacity. The capacity of 3 MWp in the solar power plant is determined because it can fulfill the load requirements in accordance with the rate of load growth without having to exceed the current carrying capacity of the conductors used in the system so that it does not cause damage to the components.

1) Solar Power Plant Specification

This simulation uses the solar power plant with a capacity of 3 MWp. In this simulation, the type of panel used is First Solar type FS-6445 with CdTe (Cadmium Telluride) thin-film material. The reason for using this type of panel is its specifications that use the latest technology so that the panel power is valued at 445 Watt / Panel and thus can produce efficiency of 18%. Detail mechanical description of solar panel FS-6445 is explained in **Table 2**.

Table 2. Mechanical Description of Solar Panel FS-6445 [7]

Characteristics	Mechanical Description
Length	2.009 m
Width	1.232 m
Thickness	49 mm
Area	2.47 m^2
Module Weight	36 kg
Leadwire	2.5 mm^2, 720 mm (+) & Bulkhead (-)
Connectors	MC4-EVO 2 or alternate
Bypass Diode	N/A
Cell Type	Thin film CdTe semiconductor, up to 264 cells
Frame Material	Anodized Aluminium
Front Glass	2.8 mm heat strengthened, Series 6A™ includes anti-reflective coating
Back Glass	2.2 mm heat strengthened
Encapsulation	Laminate material with edge seal
Frame to Glass Adhesive	Silicone
Load Rating	2,400 Pa

To fulfill the desired capacity criteria, which is 3 MWp, there are 6,818 units is needed (14 panels of series and 487 panels of parallel). The simulation is carried out on the average condition of solar irradiation in X City of 818 W / m^2.

2) Inverter Specification

The efficiency of the inverter depends very much on its relative load. Efficiency almost reaches its maximum value when the power is worth 30% of nominal. The efficiency value can be reduced at the low power point due to technical losses in the system and the inverter self-operating power. To increase the value of efficiency at low power can be done by reducing the capacity of the inverter (undersize inverter) on the solar power plant system because the inverter efficiency on the solar power plant is not constant but depends on the inverter loading ratio [8].

In this simulation, the inverter capacity is reduced to 0.75 of the solar power plant total capacity. Since the capacity of the 3 MWp solar power plant with the assumption that the system works at the optimum point is 3 MW, the inverter capacity used is 2.25 MW. The determination of this value is also based on the assumption that the load will not always be in peak condition so it is expected that the capacity can work optimally without lacking capacity value. **Table 3** shows the specifications of the inverter used in the simulation.

Table 3. Inverter Characteristics in Solar Power Plant System

Characteristics	Value
DC Rating Power	2.250 MW
Input Voltage (DC)	2.560 V
AC Rating Power	2.025 MVA
Output Voltage (AC)	0.400 kV

3) Transformer Specification

In this simulation, all transformers used are step-up transformer to increase the voltage level. For the X City electrical system, the transformer raises the voltage level from 6.3 kV to 20 kV. The capacity of each transformer varies according to the capacity of the connected generator, starting from 1.25 MVA to 7 MVA.

The solar power plant system also uses a step-up transformer so that the interconnection with a 20 kV medium-voltage network can run synchronously. **Table 4** explains the specifications of the transformer used in the solar power plant system.

Table 4. Transformer Characteristics in Solar Power Plant System

Characteristics	Value
Rating Power	4 MVA
Frequency	50 Hz
Voltage Capacity (primary)	0.4 kV
Voltage Capacity (secondary)	20 kV

4) Solar Power Plant Placement

The installation of the solar power plant requires an adequate location both in terms of distance and land availability so that the installation of the solar power plant systems is more efficient and economical. In this

simulation, the solar power plant system is placed 1.07 km away from the interconnection point, which is Bus 4. At that distance, there is a vacant land area of 16.66 Ha which can be used as the location of the solar power plant system.

Table 5. Solar Panel Type and Its Area [9]

Cell Material	Module Efficiency	Surface Area Need for 1 kWp
Monocrystalline silicon	13-19%	5-8 m^2
Polycrystalline silicon	11-15%	7-9 m^2
Micromorphous tandem cell (a-Si/μc-Si)	8-10%	10-12 m^2
Thin-film copper-indium/gallium-sulfur/diselenide (CI/GS/Se)	10-12%	8-10 m^2
Thin-film cadmium telluride (CdTe)	9-11%	9-11 m^2
Amorphous silicon (a-Si)	5-8%	13-20 m^2

To determine the total land area needed in this simulation, the surface area of the solar panel is used based on the type of material used as seen in **Table 5**. The type of material used in this simulation is thin-film CdTe, therefore a surface area of 9-11 m^2 is required for every 1 kWp. With the solar power plant capacity of 3 MWp and it is assumed that the surface area used is the largest (11 m^2), then the amount of land needed can be calculated as follows:

$$Land\ Area = \frac{Peak\ Power}{1\ kWp} \times Panel\ Surface\ Area\ [m^2] \tag{1}$$

$$Land\ Area = 3,000\ \times 11m^2 =\ 33,000\ m^2 = 3.3\ Ha \tag{2}$$

Based on equation (2), it can be concluded that the maximum land requirement for the installation of a 3 MWp solar power plant system is 3.3 Ha. Meanwhile, the potential land that can be used is 16.66 Ha. Therefore, the location that has been planned is very appropriate because the distance is not too far from the interconnection point and also has sufficient land area to install the solar power plant in accordance with the plan. The interconnection location in ETAP 12.6.0 is shown in **Figure 5**.

III. RESULTS AND DISCUSSION

A. Load Flow Simulation

1) *Scenario 1A (Before 3 MWp Solar Power Plant is Interconnected to the X City 20 kV Medium-Voltage Network System)*

The results of this scenario show the real condition of the X City electricity system, where the source of supply comes only from PLN and private power plants,

and not connected yet to the solar power plant system that has been designed. The interconnection location of 3 MWp solar power plant with 20 kV network of X City is illustrated in **Figure 3**.

**Table 6.** Inter Bus Load Flow in Scenario 1A

From Bus	To Bus	Active Power [MW]	Reactive Power [MVAR]
Bus 3	Bus 1	1.338	0.828
Bus 3	Bus 2	1.62	1.003
Bus 4	Bus 3	0.336	2.121
Bus 8	Bus 4	1.399	0.344
Bus 9	Bus 4	0.034	0.76
Bus 9	Bus 6	2.362	1.214
Bus 5	Bus 6	0.794	0.58
Bus 6	Bus 7	0.562	0.384

Table 6 shows the value of active power and reactive power flowing from one bus to another bus. Besides the power flow, other data obtained from this simulation are the voltage values on each bus. According to the PLN Standard (SPLN) 1: 1978, variations in service voltage as a result of voltage losses due to changes in load and voltage regulation, allowed a maximum of + 5% and a minimum of -10% of nominal voltage [10]. In this simulation, the nominal voltage on all buses is 20 kV.

Table 7. Bus Voltage in Scenario 1A

Bus	Bus Voltage [kV]	Bus Voltage [%]
Bus 1	19.359	96.796
Bus 2	19.394	96.972
Bus 3	19.484	97.419
Bus 4	19.544	97.722
Bus 5	19.034	95.172
Bus 6	18.853	94.265
Bus 7	18.679	93.396
Bus 8	19.988	99.942
Bus 9	19.702	98.511

From the data in **Table 7**, the voltage on each bus is in good condition. This is evidenced by the absence of bus voltage values that exceed the limits set by SPLN 1: 1978. From **Table 7** it can also be concluded that the voltage value on each bus is below 100% due to a voltage drop. This relates to the presence of reactive components such as transformers, loads, and cables used in the system.
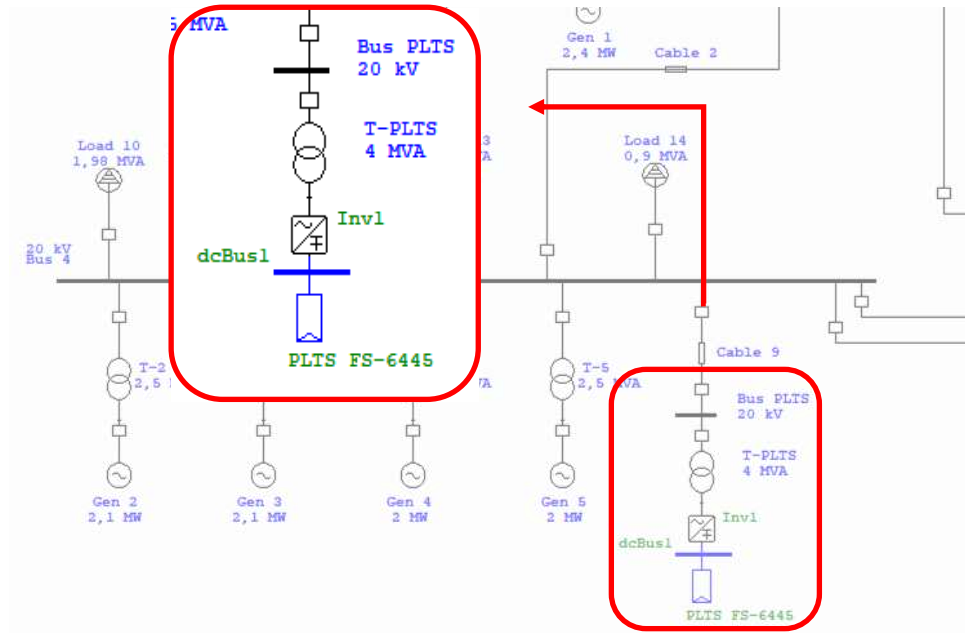
Figure 3. Interconnection Location of 3 MWp Solar Power Plant with 20 kV Medium-Voltage Network of X City

Other data results obtained in power flow simulation are loading data on components such as transformers and cables. The maximum capability limit for loading is 100%. From **Table 8**, it can be concluded that the loading value on each component is considered in good condition because it is still below 100%.

Table 8. Loading in Scenario 1A

Name	Loading [%]
Cable	
Cable 1	24.35
Cable 2	27.35
Cable 3	20.11
Cable 4	12.86
Cable 5	33.55
Cable 6	9.62
Cable 7	8.73
Cable 8	17.94
Transformer	
T 1	85.30
T 2 – T 5	66.40
T 6 – T 7	19.70
T 8 – T 14	6.90
T 15 – T 22	12.90

2) Scenario 1B (After 3 MWp Solar Power Plant is Interconnected to the X City 20 kV Medium-Voltage Network System)

In this scenario, the 3 MWp solar power plant system is already connected to the X City electricity system, precisely located on Bus 4. To produce maximum power, the solar power plant is assumed to operate when solar irradiation is at peak conditions, which is 818 W / m^2.

Table 9. Inter Bus Load Flow in Scenario 1B

From Bus	To Bus	Active Power [MW]	Reactive Power [MVAR]
Bus 3	Bus 1	1.340	0.829
Bus 3	Bus 2	1.622	1.004
Bus 4	Bus 3	3.282	1.943
Bus 8	Bus 4	1.399	0.344
Bus 9	Bus 4	0.025	0.755
Bus 9	Bus 6	2.371	1.220
Bus 5	Bus 6	0.794	0.580
Bus 6	Bus 7	0.564	0.349

Table 9 shows the simulation results in the form of power flow from one bus to another in scenario 1B, which 3 MWp the solar power plant has been connected to the system. The direction of power flow in scenario 1B is still the same as scenario 1A. Most of the active and reactive power values in scenario 1B increase with a small value compared to the data in scenario 1A due to the additional power supply from the solar power plant system.

Table 10. Bus Voltage in Scenario 1B

Bus	Bus Voltage [kV]	Bus Voltage [%]
Bus 1	19.418	97.091
Bus 2	19.453	97.266
Bus 3	19.542	97.712
Bus 4	19.730	98.648
Bus 5	19.216	96.081
Bus 6	19.037	95.183

Bus	Bus Voltage [kV]	Bus Voltage [%]
Bus 7	18.864	94.318
Bus 8	20.170	100.849
Bus 9	19.881	99.407

According to **Table 10**, all buses have increased voltage after being connected to the solar power plant system. The existence of a 3 MWp solar power plant that is connected to the X City electrical system can help improve the system voltage on each bus with a value that is still in accordance with the standards in SPLN 1: 1978, which is minimum -10% and maximum + 5% of nominal voltage [10].

Table 11. Loading in Scenario 1B

Name	Loading [%]
Cable	
Cable 1	24.30
Cable 2	48.12
Cable 3	20.07
Cable 4	12.74
Cable 5	33.39
Cable 6	9.46
Cable 7	8.67
Cable 8	17.78
Transformer	
T 1	48.10
T 2 – T 5	66.40
T 6 – T 7	19.70
T 8 – T 14	6.90
T 15 – T 22	12.90
T PLTS	74.60

Table 11 shows the results of loading on the cable and transformer components after the 3 MWp solar power plant system is connected to the X City electrical system. From the table, it can be concluded that the cables and transformers in the system are still in a decent condition after the solar power plant system is interconnected. This is evidenced by the loading value of each component that are below the maximum loading limit of 100%.

B. *Three-Phase Short Circuit Fault Simulation*

1) *Scenario 2A (Before 3 MWp Solar Power Plant is Interconnected to the X City 20 kV Medium-Voltage Network System)*

In this scenario, the data obtained from the simulation is the real result of a short circuit fault in X City because there is no integration of the solar power plant system. The data that were taken in the form of short-circuit fault current (in units of kA) are closely related to the protection system used in the electrical system. That is because the protection system has a short-circuit breaking

capacity value, where the protection system will break the short-circuit fault current if it has exceeded that capacity [11]. In this simulation, the breaking capacity of the short circuit faults in the circuit breaker is 25 kA.

Table 12. Short Circuit Fault Current in Scenario 2A

Bus	Short Circuit Fault Current [kA]
Bus 1	3.931
Bus 2	4.526
Bus 3	5.675
Bus 4	6.695
Bus 5	1.686
Bus 6	2.422
Bus 7	1.472
Bus 8	4.125
Bus 9	4.848

Based on the results in **Table 12**, each bus has a varying short-circuit fault current value. This happens because of differences in impedance of each component such as generators, cables, and transformers. Even so, the entire value of the short circuit fault current is still far below the value of the short-circuit breaking capacity (25 kA). Therefore, the condition of the X City electrical system in terms of short circuit fault can be considered as in good condition.

2) *Scenario 2B (After 3 MWp Solar Power Plant is Interconnected to the X City 20 kV Medium-Voltage Network System)*

In this scenario, the solar power plant system has been connected to the X City electrical system, precisely located on Bus 4. To produce maximum power, the solar power plant is assumed to operate when solar irradiation is at peak conditions, which is 818 W / m^2. The following is the result of the simulation in scenario 2B in the form of a short circuit fault current.

Table 13. Short Circuit Fault Current in Scenario 2B

Bus	Short Circuit Fault Current [kA]
Bus 1	3.930
Bus 2	4.527
Bus 3	5.686
Bus 4	6.732
Bus 5	1.686
Bus 6	2.421
Bus 7	1.472
Bus 8	4.120
Bus 9	4.843

From the results of **Table 13**, it can be concluded that the value of the short circuit fault current after the connection with the solar power plant has varied. Even so,

the changes experienced did not show significant numbers. The simulation results in scenario 2B also show that all buses are still in good condition based on the three-phase short circuit fault result because the value is still far below the maximum limit of the short circuit fault current (25 kA).

IV. CONCLUSION

Based on the results of simulations and analysis that have been executed in the study, the following conclusions can be drawn as some points.

The results of the power flow analysis show that the interconnection of the 3 MWp solar power plant system with the X City electricity system caused an increase in active power supply by 0.002-2.946 MW and reactive power by 0.001-0.006 MVAR, an increase in bus voltage by 0.293%-0.926%, as well as the percentage of loading valued constant and change (an increase of 20.77% and a decrease of 0.04% -0.16%). The results obtained are in accordance with applicable standards, namely the SPLN 1: 1978 bus voltage standard of 90% -105% and the loading standard that is under 100%.

The results of the short circuit fault analysis show that the interconnection of the 3 MWp solar power plant system with the X City electrical system caused the three-phase short circuit fault value to increase from 1 to 37 A as well as a decrease with an insignificant value. The results obtained are still below the short circuit breaking capacity, which is 25 kA so that it does not cause excess voltage.

Based on the results of the power flow analysis (Number 1) and the results of the analysis of short circuit faults (Number 2), the 3 MWp solar power plant interconnection plan with the X City 20 kV medium-voltage network system is feasible.

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