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Interconnection Study in Utilizing of Solar Energy for 150 MW Photovoltaic Power Generation through 150 kV Transmission Line

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ABSTRACT- The interconnection of utility-scale photovoltaic (PV) power plants with the electric grid is a crucial factor that requires comprehensive analysis and assessment. The focus of this research article is on a specific photovoltaic (PV) power plant that is planned for construction in the X Power System located in Indonesia which has 150 MW capacity which has intermittent behavior, experiencing fluctuations in power generation based on the availability of sunlight and the cloud movement. The objective of this paper is to explore the feasibility, technical prerequisites, and potential solutions for the successful integration of the PV power plant into the existing power system. Multiple investigations will be carried out, which is Load Flow, Short-Circuit, and Transient Stability analyses, with the aim of assessing the consequences of linking the PV power plant to the existing power system. Consequently, it is vital to model the X power system conditions prior to the interconnection process. Moreover, modeling an intermittent PV power plant necessitates different approaches compared to conventional power plants. According to the research findings from load flow analysis, the voltage levels near the interconnection point, both prior to and after linking the PV Power Plant, remain within permissible bounds of +5% and -10%. Furthermore, there are no constraints on the load capacity of the transmission lines and Interbus Transformers (IBT) either prior to or following the integration of the PV Power Plant. The short-circuit current around the point of interconnection experiences a marginal increase, and it is advisable to employ circuit breakers (CB) rated at 40 kA for both the PV Power Plant and the switching station. Furthermore, the power system exhibits resilience in preserving its stability, even in scenarios involving abrupt power loss or intermittent generation from the PV Power Plant. These situations can result from unexpected outages or variations in solar radiation. The interconnection of the 150 MW PV Power Plant can be implemented without significant adverse effects on the system's voltage, loading capacity, and stability.

Keywords: PV power plant, interconnection, cloud movement, intermittent.

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1. INTRODUCTION

The interconnection of large photovoltaic (PV) power plants into the electrical grid is a crucial element demanding comprehensive scrutiny and assessment [1]. With the increasing global demand for clean and sustainable energy, PV power plants have emerged as a viable solution for electricity generation [2], [3].

The PV Power Plant which is mainly discussed in this paper is one of the power plants that will be constructed in X Power System in Indonesia. The capacity of the PV Power Plant is 150 MW and it will operate by delivering power to the X Power System through a 150 kV transmission line to the switching station between KS and HI Substation. The PV Power Plant that will be interconnected is an on-grid power plant, which does not have storage (battery) to store the generated electricity. The 150 MW PV Power Plant generally operates during the daytime for approximately 5 to 6 hours per day [4], [5].

PV Power Plant has intermittent characteristics, where it will fluctuate based on the presence or absence of sunlight or when clouds pass and cover the solar panel field [6],[8]. Hence, the impact of these intermittent characteristics becomes an important aspect of this interconnection study or grid impact study [7], [9]. The objective of this interconnection investigation is to evaluate the viability and examine the stability of incorporating the 150 MW PV power plant into an established electrical grid or power system [10],[12].

The interconnection research covered in references [11], [13], [14] primarily addresses the integration of small-scale PV Power Plants into distribution systems. There are also various utility-scale interconnections presented in references [1], [15]. However, the focus of this paper is on conducting an interconnection study for a substantial 150 MW PV power plant, taking into account its intermittent operation due to factors like cloud movement. This study aims to explore the feasibility, technical prerequisites, and potential solutions for its successful integration into the electrical grid. The study encompasses multiple analyses, including Load Flow, Short-Circuit, and Transient Stability assessments:

1. Load Flow Study
2. Short-Circuit Study
3. Transient Stability Study

The impact of PV power plant interconnection will be evaluated in each study. Therefore, modeling the power system conditions before the interconnection is also crucial. Additionally, modeling an intermittent PV power plant differs from conventional power plants.

Overall, the interconnection study aims to provide valuable insights into the interconnection process, compliance with applicable grid codes and standards, and the overall stability and reliability of the system. This study enhances the understanding of efficient interconnection procedures for sizeable PV power plants and acts as a valuable point of reference for forthcoming projects within this field.

2. MATERIALS AND METHODS

2.1 Key Assumptions

It's important to mention that all studies, which encompass system modeling, were conducted using the DIgSILENT Power Factory software, with the exception of the PV plant design study that employed PVSyst. Nevertheless, the study relies on the following critical key assumptions:

1. The modeling of the X power system in the interconnection year is based on the National Electricity Supply Business Plan Document in Indonesia [16].
2. This Interconnection Study is conducted during the peak daytime load using the calculation of scaling factor which is equal to 0.9 times the Night-time Peak Load. The load data is also based on [16].
3. The PV power plant is capable of producing a maximum power of 150 MW
4. The power plants dispatch is based on merit order (Optimal Power Flow) as outlined in *table 1*.
5. Each type of power plant is assumed to use primary control as described in *table 1*.

Table 1: Merit Order and Primary Control of Generator

Merit Order	Power Plant	AVR	GOV
1	Coal	IEEET1	TGOV1
2	Hydro	SCRX	HYGOV
3	Geothermal	REXSYS	IEEEG1
4	Combined-Cycle	ESST1A	GAST
5	Gas	ESST1A	GAST
6	Diesel	SEXS	DEGOV

2.2 X Power System

2.2.1 Power System Condition and Modeling

The X power system refers to the interconnected electrical grid that supplies electricity to the several regions in Indonesia. This power system is one of the largest and most important in the country, serving a significant portion of the population and supporting various industrial, commercial, and residential activities. The X Power System is divided into 5 regions. The region 1 to region 4 is on the same island, while the region 5 is on the different island.

The X power system is interconnected by 500 kV Extra High Voltage Overhead Line, 150 kV High Voltage Overhead Line, and 70 kV High Voltage Overhead Line. The regions in the X power system is interconnected with 500 kV transmission system, the backbone of the power supply X power system. The power supply power plant powers with high generation capacity in the region 1 to region 4 (eastern side) will be interconnected through the 500kV transmission line, then in the Extra High Voltage Substation, voltage level 500 kV will be lowered to 150 kV through the Inter Bus Transformer (IBT) 500/150 kV. The IBT also serves as the main supply of the 150 kV transmission system. Besides the IBT, there are also some power plant units that supply its power to the region sub-system. The power from 150 kV transmission system then will be supplied to the load centers (150 kV Substations) or be lowered to the 70 kV voltage level through IBT 150/70 kV substations and evacuated to another 70 kV substations through 70 kV transmission line.

The X Power System consists of three areas of large generation, which is the backbone of the system, on the east side, on the central, and on the western side. The power from the generation units will be evacuated to the power system through the extra high voltage 500 kV transmission lines, also high voltage 150 kV and 70 kV transmission lines.

The typical daily load curve in X power system will be shown in *figure 1*. This load curve will be considered for the modelling of the X Power System.

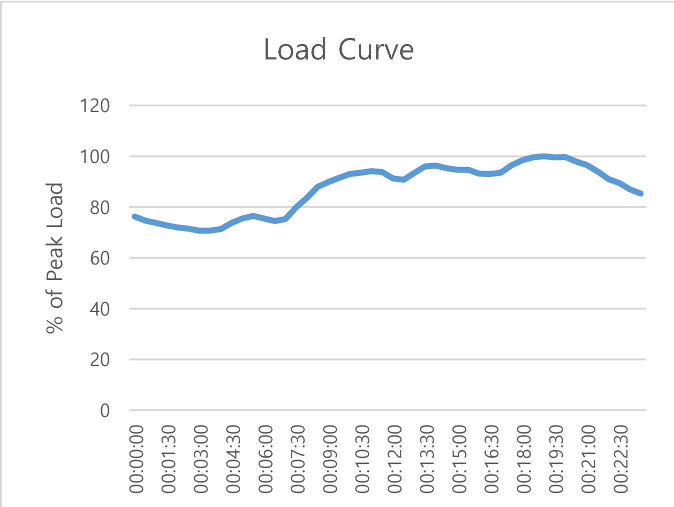

Figure 1: Typical Load Curve in X Power System

The modelling of X Power System by gathering comprehensive data on multiple aspects, including electricity demand, existing power plants, transmission lines, planned power plants, planned transmission lines, as well as the 150 MW PV power plant and its corresponding transmission lines. The modelling conducted for this study is utilizing the advanced power system software DigSILENT PowerFactory. The data that will be needed for the modelling:

- Power plant: Capacity, Type, Operating year for planned power plant, technical characteristics (if any)
- Transmission lines: Capacity, Impedance, Length, Operating year for planned transmission lines
- Substation: Voltage level, Inter Bus Transformer and/or substation transformer technical characteristics (if any), Breaker capacity (if any), Operating year for planned substation
- Load: Peak load in each substation (if any), Operating conditions (if any), Dispatch power from power plant, Transmission line status

Using the collected data, the X power system mode was developed and integrated into the power system software, which is DigSILENT Power Factory. In cases where certain data was missing, generic data was utilized. However, due to confidentiality reasons, the process of modelling, validation, and result of the X power system modelling will not be presented in this paper. However, it is worth noting that the X power system model has undergone validation by comparing its power flow results data with those of the existing power system, provided by the Indonesian government-owned corporation responsible for electric power distribution and most of the country's electricity generation.

The X-power system model in DigSILENT Power Factory consists of 188 substations situated across five regions. It involves 1983 transmission lines operating at various voltage levels, including 500 kV, 150 kV, and 70 kV. Additionally, the model comprises 284 generators (power plants) and 78 IBT (Interconnecting Bus Transformer) units rated at 500/150/66 kV. It also encompasses 1303 transformers rated at 150/20 kV (modeled as loads) and 162 transformers at 70/20 kV (also modeled as loads).

The model includes specific information on the substations, loads, transmission lines, generation, load, grid losses, installed capacity, and spinning reserve for each region which are:

- Region 1
  - No. of Substations: 272
  - No. of Loads: 520
  - No. of Transmission Lines: 688
  - Generation: 7927.63 MW, 649.14 Mvar
  - Load: 9301.07 MW, 3057.12 Mvar
  - Grid Losses: 76.63 MW, -876.12 Mvar
  - Installed Capacity: 10855.35 MW
  - Spinning Reserve: 1450.37 MW

- Region 2
  - No. of Substations: 213
  - No. of Loads: 276
  - No. of Transmission Lines: 344
  - Generation: 7764.38 MW, 2416.35 Mvar
  - Load: 7754.36 MW, 2548.73 Mvar
  - Grid Losses: 106.61 MW, 1383.58 Mvar
  - Installed Capacity: 8908.46 MW
  - Spinning Reserve: 859.62 MW

- Region 3
  - No. of Substations: 283
  - No. of Loads: 198
  - No. of Transmission Lines: 280
  - Generation: 7607.12 MW, 815.40 Mvar
  - Load: 4496.40 MW, 1477.90 Mvar
  - Grid Losses: 91.67 MW, 1067.32 Mvar
  - Installed Capacity: 8053.29 MW
  - Spinning Reserve: 56.26 MW

- Region 4
  - No. of Substations: 234
  - No. of Loads: 322
  - No. of Transmission Lines: 357
  - Generation: 5520.72 MW, 1137.62 Mvar
  - Load: 5978.94.40 MW, 1965.18 Mvar
  - Grid Losses: 125.45 MW, 959.53 Mvar
  - Installed Capacity: 6683.56 MW
  - Spinning Reserve: 759.68 MW

- Region 5
  - No. of Substations: 34
  - No. of Loads: 52
  - No. of Transmission Lines: 61
  - Generation: 284.43 MW, -35.51 Mvar
  - Load: 960.31 MW, 315.64 Mvar
  - Grid Losses: 18.33 MW, 57.19 Mvar
  - Installed Capacity: 444.00 MW
  - Spinning Reserve: 90.57 MW

2.2.2 Grid Code and Regulation

Grid Code refers to a set of technical and operational requirements, guidelines, and standards that govern the operation and interconnection of power generation units, transmission lines, distribution systems, and other grid components. It represents a set of regulations or a document created by the regulatory authority or grid operator to guarantee the secure, reliable, and effective functioning of the power grid. In X Power System, the allowable operational limits based on the Grid Code regulations for the power system network [17] for voltage limit are presented in *table 2.*

Table 2: Power System Voltage Limit [17]

Nominal Voltage (kV)	Normal Condition
500 kV	+5%, -10%
275 kV	+5%, -10%
150 kV	+5%, -10%
66 kV	+5%, -10%
30 kV	+5%, -10%

On the other hand, concerning the transient stability analysis, it's stipulated by the Grid Code that the frequency deviation must adhere to the condition of 49.0 Hz $\leq f \leq$ 51.0 Hz, with '*f*' representing the frequency. In this case, the specified range is suitable for continuous operation, and factors affecting frequency are determined by the power output of a generator relative to the load demand. Therefore, it is necessary to

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regulate the generation and consumption of power to maintain the frequency within the specified variable range.

2.3 PV Power Plant Modelling

2.3.1 Model of Internal System

The PV Power plant was modeled in DIgSILENT PowerFactory software. The model of the plant utilizes the general PV models of DIgSILENT PowerFactory software. The model of the PV plant includes models of Solar Radiation, Temperature, Photovoltaic Model, DC Busbar and Capacitor Model, Controller, and Static Generator. The Photovoltaic Model includes the detection of Array Voltage, Number of Serial and Parallel Module of Solar Panel, and the details of the PV Module.

The model of Photovoltaic panel receives the solar radiation and temperature to produce a current (I_{array}) to the DC Busbar and the Capacitor Model with the reference of the voltage of the array (U_{array}). Then the controller oversees the MPPT (Maximum Power Point Tracking) by utilizing data of AC Voltage, PV Array Voltage, and Active Power Reduction. The controller yields the reference for the Static Generator to produce the Power to the system. The details of the blocks of the model are presented *figure 2*.

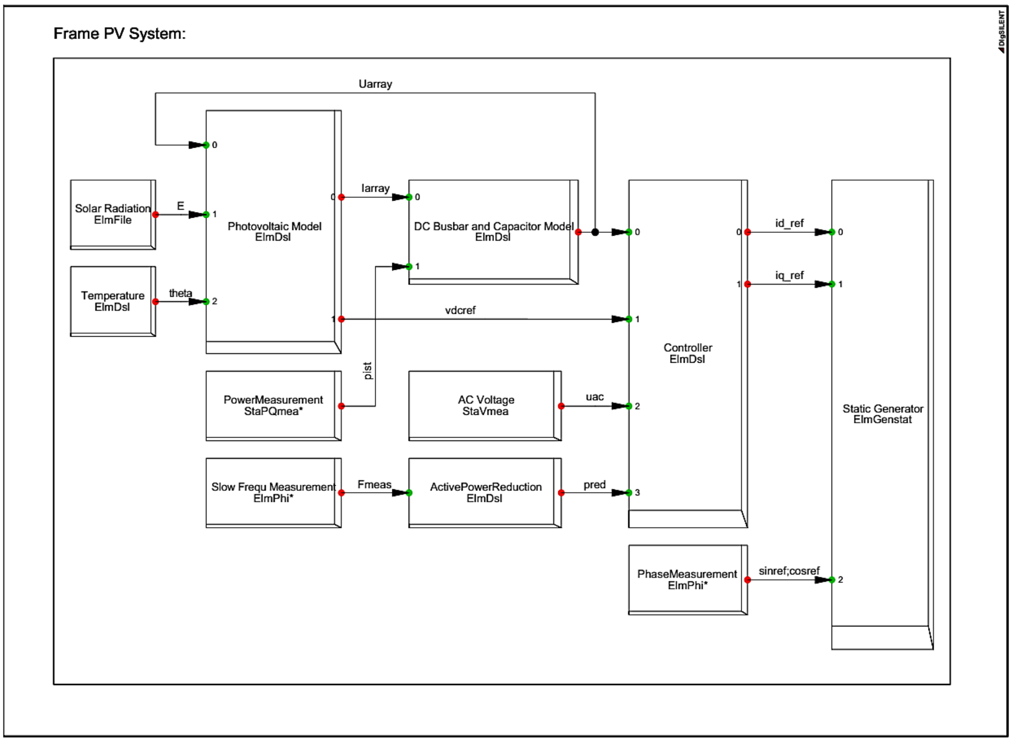

Figure 2: Frame Model of PV System

The Maximum Power Point Tracking function (I_{mpp} = 4.58 A and V_{mpp} = 35 V), Short Circuit Current (I_{sc} = 5 A), and Open Circuit Voltage (V_{oc} = 43.8 V).

The block functions of the PV Model which include PV Array, DC Busbar and Capacitor, Controller, and Active Power Reduction is utilizing the typical model of provided by the power system software. However, the inputted parameters for each block functions of the PV Model are including PV Array, DC Busbar and Capacitor, Controller, and Active Power Reduction is presented in *table 3* to *table 6* respectively.

Table 3: PV Array Block Diagram Parameter

Parameter	Value	Unit	Annotation
Ul0	43.8	[V]	Open-circuit Voltage (STC) of Module
Umpp0	35	[V]	MPP Voltage (STC) of Module
Impp0	4.58	[A]	MPP Current (STC) of Module

Ik0	5	[A]	Short-circuit Current (STC) of Module
au	-0.0039	[1/K]	Temperature correction factor (voltage)
ai	0.0004	[1/K]	Temperature correction factor (current)
nSerialModules	20	Number	
nParallelModules	140	Number	
Tr	0	[s]	Time Constant of Module

Table 4: DC Busbar and Capacitor Block Diagram Parameter

Parameter	Value	Unit	Annotation
Capacity	0.0172	[s]	Time constant of the capacitor on DC busbar
Udc0	700	[V]	Initial DC-voltage
UdcN	1	[kV]	Nominal DC Voltage
Pnen	0.5	[MW]	Rated Power

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Table 5: Controller Block Diagram Parameter

Parameter	Value	Unit	Annotation
Kp	0.005	[-]	Gain, Active Power PI-Controller
Tip	0.03	[s]	Integration Time Constant, Active Power PI-Controller)
Tr	0.001	[s]	Measurement Delay
Tmpp	5	[s]	Time Delay MPP-Tracking
deadband	0.1	[pu]	Deadband for AC Voltg. Support
droop	2	[-]	Static for AC Voltg. Support
i_EEG	1		0 = acc. TC2007; 1 = acc. SDLWindV
id_min	0	[p.u.]	Min. Active Current Limit
U_min	333	[V]	Minimal allowed DC-voltage
iq_min	-1	[pu]	Min. Reactive Current Limit
id_max	1	[p.u.]	Max. Active Current Limit
iq_max	1	[pu]	Max. Reactive Current Limit
maxAbsCur	1	[pu]	Max. allowed absolute current
maxIq	1	[pu]	Max.abs reactive current in normal operation

Table 6: Active Power Reduction Block Diagram Parameter

Parameter	Value	Unit	Annotation
fUp	50.2	[Hz]	Start of Act. Power Reduction
fLow	50.05	[Hz]	End of Act. Power Reduction
gradient	40	[%/Hz]	The gradient of Act. Power Reduction
Tfilter	0.01	[s]	PT1-Filter Time Constant

2.3.2 PV Power Plant Configuration

PV Farm in Bali will have 9 big clusters in 20 kV Voltage Level, each big cluster connected to 3-winding transformers 20 kV / 0.4 kV with a capacity of 2x2500 kVA. The 3-winding transformers will transfer the power from PV in the smaller cluster, so that, each 3-winding transformers will have 3 smaller clusters in 0.4 kV voltage level with a capacity of 60 MVA each small cluster. The smaller clusters in 20 kV voltage level will connect to the PV Farm bus in 150 kV voltage level through Step-Up Transformers 150/20 kV with a capacity of 60 MVA. On the other hand, the power plant will interconnect to the X power system via a Switching Station (which is the interconnection point) through ACSR 4xZebra 2cct with 20 km in length. The PV Power Plant configuration is described in *figure 3*.

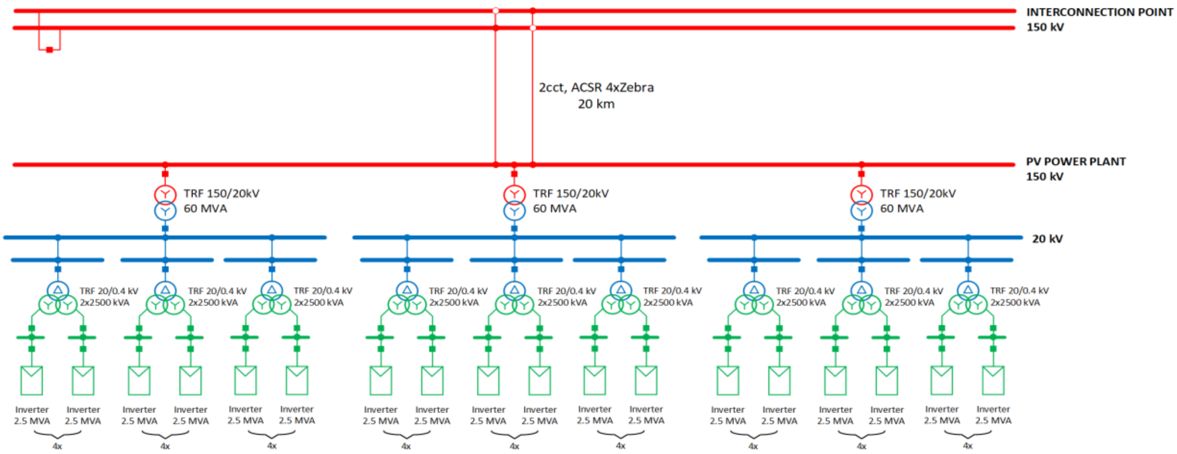

Figure 3: PV Power Plant Configuration

2.4 Load Flow Study

Load flow analysis is a study aimed at obtaining information about load flow analysis under specific system operating conditions. The main objective of this analysis is to assess the system's operational effectiveness and gauge its performance under specific generation conditions [18]. Load flow analysis will be conducted for the system conditions during the PV power plant's operating hours, specifically during the peak daytime load conditions. This power flow study will examine the impact of power flow changes around the interconnection point before and after the PV power plant interconnection [11], [13].

The load flow simulation uses an AC load flow calculation method that's both balanced and positive sequence. It also factors in the generators' reactive power limits for control and pays attention to how the loads depend on voltage.

In this study, the modelling of the X Power System will cover its entire power system, as explained before. However, the load flow study results will only presented 2 levels from the interconnection point of the 150 MW PV power plant on 2 scenarios:

1. Before interconnection of 150 MW PV Power Plant
2. After interconnection of 150 MW PV Power Plant
3. The load flow study only considering the peak day time load condition in both scenarios and the PV power plant output is assumed to be maximum in the peak daytime load condition.

2.5 Short-Circuit Study

A short circuit analysis holds significant importance, particularly in the planning, building, and development of the power network system. The data derived from this study is instrumental in determining relay configurations and the rating of circuit breakers (CB). The selection of CBs for the power system hinges not solely on the current which its carry during regular operation but also on the peak current that can transpire briefly in the event of a fault [19],[21].

The Short Circuit Study is performed to assess the impact of PV power plant interconnection on short circuit levels at each substation bus in the vicinity of the interconnection point and to ascertain whether existing CB capacity limits are exceeded.

In the short-circuit simulation, the IEC 60909 method is used, specifically the 3-Phase Short-Circuit Fault Type, to determine the maximum short-circuit current. Additionally, when performing the short-circuit simulation, only substations located within two levels from the interconnection point of the 150 MW PV Power Plant are considered.

The short circuit analysis will be executed under the peak daytime conditions. The subsequent parameters will be taken into account [22] [23]:

- Initial short-circuit current (Ik") the r.m.s. (root mean square) value of the AC symmetrical current that flows through a circuit immediately after a short circuit occurs
- Initial short-circuit power (Sk")
- Peak short-circuit current (ip) The maximum instantaneous value of short circuit current
- Breaking short-circuit current (Ib) Commonly known as the breaking capacity or breaking current rating, it refers to the current at which a circuit breaker can interrupt without causing damage or creating an electric arc with an unsustainable duration for the equipment.
- Short-Circuit breaking power (Sb)
- Steady-state short-circuit current (Ik) The value of the residual root mean square (r.m.s.) current after the reduction of current due to transient phenomena.
- Thermal equivalent Short-Circuit Current (Ith) The value of the root mean square (r.m.s.) short-circuit current that has the same thermal effect and duration as the actual short-circuit current, which may contain a DC component. It can be defined as the thermal short-circuit current limit within a 1-second range.

Nonetheless, when assessing the circuit breakers (CB) capacity, the main emphasis will be placed on two key factors: the Breaking short-circuit current (Ib) and the Short-Circuit breaking power (Sb).

2.6 Transient Stability Study

Transient Stability Analysis is conducted to assess the intermittent effects of on-grid PV power plants on the interconnected grid system [24]. The key parameters include the RMS (Root Mean Square) value of the system frequency and the voltage at the interconnection point under various scenario changes resulting from the integration of on-grid PV power plants.

The transient stability study in this research focus in frequency stability which is a part of transient stability analysis that examines the response of the power system frequency during changes in the output of the PV power plants due to their intermittent nature.

In transient simulations in the DigSILENT Power Factory software, the method utilizied RMS values (electromechanical transients). The network representation remains balanced and positive sequence.

In this paper, the Transient Stability Study will consider the system frequency response for the following events:

1. PV power plant losing generation of 150 MW from 100% to 0% suddenly.
2. PV power plant losing generation of 150 MW from 100% to 25% (within 57 seconds) as a representation of decreased PV generation due to reduced extreme sunlight radiation caused by cloud movement.

For the event of the PV power plant losing generation of 150 MW from 100% to 25%, the value of 57 seconds is obtained by calculating how quickly the clouds will cover the sun as depicted in *figure 4*. As such, the necessary data and presumptions for calculating the duration it takes for PV generation to decline from 100% to 25% include the following:

- Cloud speed = 18 m/s
- Cloud height = 2000 m
- Cloud radius = 3 km
- Area of the PV power plant = ±181 hectares
- Side length of the PV power plant = 1370 m
- Power gradient = 1.97 MW/s

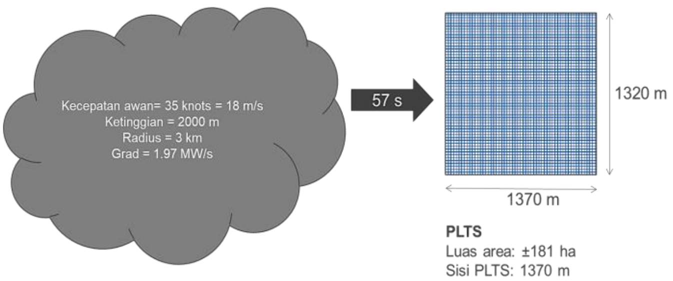

Figure 4: Cloud Movement Illustration

The cloud speed derived from the NASA Surface meteorology and Solar Energy: RETScreen Data which is measure in 10 m height. The cloud is assumed to be in 2000 m height based on [25]. So that the measurement in 10 m height will be transferred to 2000 m using the equation (1) which is the logarithmic wind profile law [26].

$$v_2 = v_1 \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \quad (1)$$

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The reference speed, denoted as v_1 (based on the data) and measured at the reference height h_1 (10 m), contrast with v_2, representing the wind speed at height h_2 (2000 m). Additionally, z_0 denotes the roughness length and is assumed to belong to roughness class 4 based on the *table 7* which is categorize as large cities with tall buildings and skyscrapers, and will be serve as a worst-case condition for this kind of event.

Table 7: Roughness Class [26]

Roughness Class	Roughness length Z0	unit
0	0,0002	m
0,5	0,0024	m
1	0,03	m
1,5	0,055	m
2	0,1	m
2,5	0,2	m
3	0,4	m
3,5	0,6	m
4	1,6	m

On the other hand, the radius of the cloud assumed to be 3 km and the area of power plant is assumed, based on the existing data, to be 181 ha with 1320 x 1370 m. This condition shows that the radius of the cloud can cover the entire PV power plant area. So that the power gradient can be calculated utilizing *equation (2).*

$$P_{grad} = \frac{P_{max} \cdot v_{cloud}}{L} \tag{2}$$

The P_{grad} represents the power gradient in MW/s, while P_{max} signifies the maximum nominal capacity of the PV Power Plant, set at 150 MW. The v_{cloud} is the cloud speed at the 2000 m height. The L is the side length of the PV Power Plant. So that the power gradient will resulting 1.97 MW/s. From the power gradient, the time for the PV Power Plant to 100% to 25% loss of generation due to cloud movement can be calculated utilizing *equation (3)* which resulting in 57 s.

$$t_{loss} = \frac{P_{max} \cdot (100\% - 25\%)}{P_{grad}} \tag{3}$$

The transient stability study will consider the system frequency as the main parameter. The frequency then will be compared to the applicable grid code. If there are any grid code violation, mitigation will be recommended to comply to the grid code.

3. RESULTS

This section will present the results of the simulations conducted based on the previously outlined methodology. The analysis is conducted to evaluate the technical performance of the X power system following the interconnection of a 150 MW PV power plant.

3.1 Load Flow Study Result

As mentioned before, the considered substation will be 2 level from the interconnection point. In this case, the 150 MW PV power plant will deliver its power to the power grid through a Switching Station. Therefore, the Switching Station will act as the point of interconnection. Regarding the load flow analysis, particular simulation outcomes are acquired, such as voltage and current profiles, power distribution, and so forth. The result of load flow study in the X power system at the year of interconnection before the interconnection of the PV power plant shown in *figure 5*. However, after interconnection there are difference in the load flow, which is shown in *figure 6.*

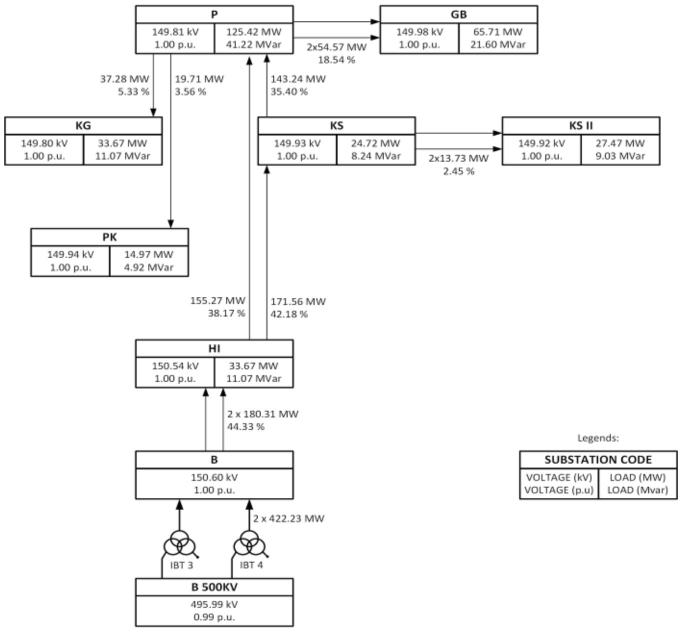

Figure 5. Load Flow Before Interconnection of 150 MW Power Plant

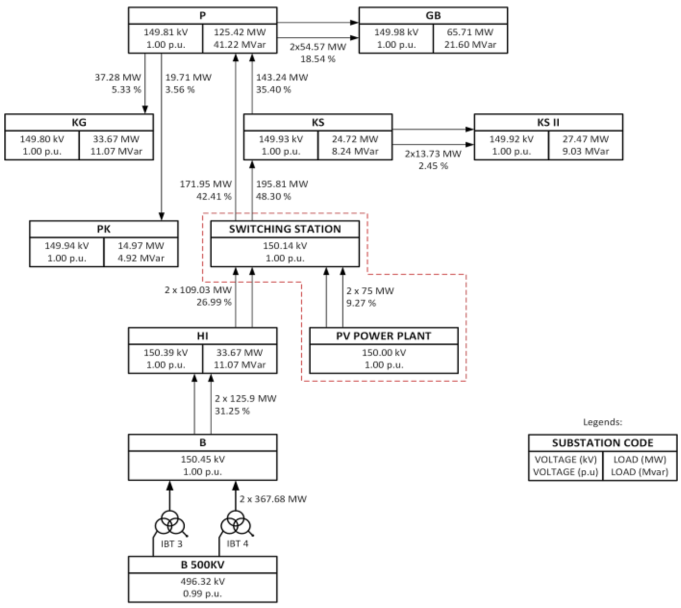

Figure 6: Load Flow After Interconnection of 150 MW Power Plant

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3.2 Short-Circuit Study Result

The output of the short circuit simulation provide data on the three-phase short circuit current levels at the substations situated near the interconnection point of the 150 MW PV Power Plant. This analysis is limited to substations located within two levels of the interconnection point, as shown in *table 8*.

Table 8: Short-Circuit Current Result

150 kV SUBSTATION	BEFORE INTERCONNECTION				AFTER INTERCONECCTION			
	Ik" (kA)	ip (kA)	Ib (kA)	Ik (kA)	Ik" (kA)	ip (kA)	Ib (kA)	Ik (kA)
B	31.79	85.77	31.79	31.79	32.55	87.66	32.55	32.55
GB	15.20	40.18	15.20	15.20	15.39	40.67	15.39	15.39
HI	30.74	82.44	30.74	30.74	31.50	84.34	31.50	31.50
KS	22.72	58.27	22.72	22.72	23.78	61.02	23.78	23.78
KS II	21.97	56.03	21.97	21.97	22.95	58.56	22.95	22.95
KG	23.04	58.24	23.04	23.04	23.47	59.22	23.47	23.47
P	25.33	65.47	25.33	25.33	25.88	66.77	25.88	25.88
PK	25.49	66.13	25.49	25.49	25.99	67.28	25.99	25.99
SWITCHING STATION	-	-	-	-	28.12	73.82	28.12	28.12
PV Power Plant	-	-	-	-	22.16	57.57	22.16	22.16

3.3 Transient Stability Study Result

Transient Stability Analysis will examine the system frequency response for the following events:

1. PV power plant losing generation of 150 MW from 100% to 0% suddenly.
2. PV power plant losing generation of 150 MW from 100% to 25% (within 57 seconds) as a representation of decreased PV generation due to reduced extreme sunlight radiation caused by cloud movement.

The simulation results of the transient stability study (system frequency response) during the event of sudden loss of 150 MW generation from 100% to 0% for the PV Power Plant are shown in *figure 7*.

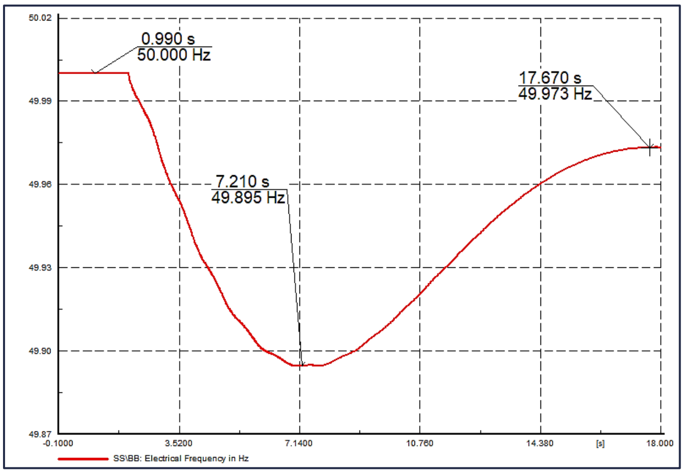

Figure 7: System Frequency (Hz) when the PV Power Plant suddenly loses 150 MW generation from 100% to 0%

The simulation results of the transient stability study (considering the response of solar radiation and system frequency) during the gradual loss of 150 MW generation from 100% to 25% within 57 seconds by the PV Power Plant are shown in *figure 8* and *figure 9*.

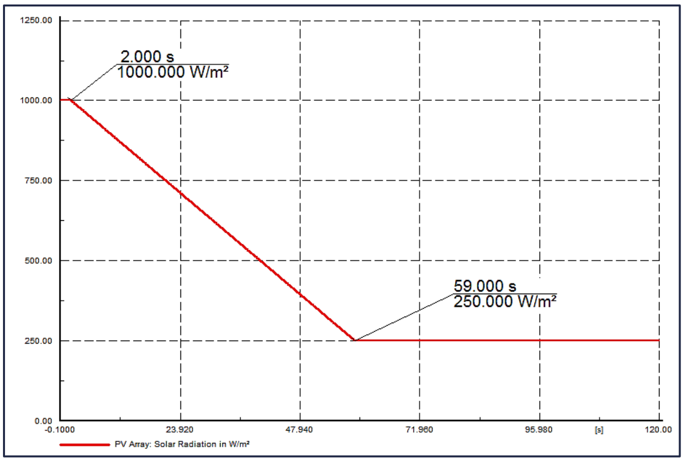

Figure 8: Solar Radiation (W/m2) when the PV Power Plant loses 150 MW generation from 100% to 25% within 57 seconds

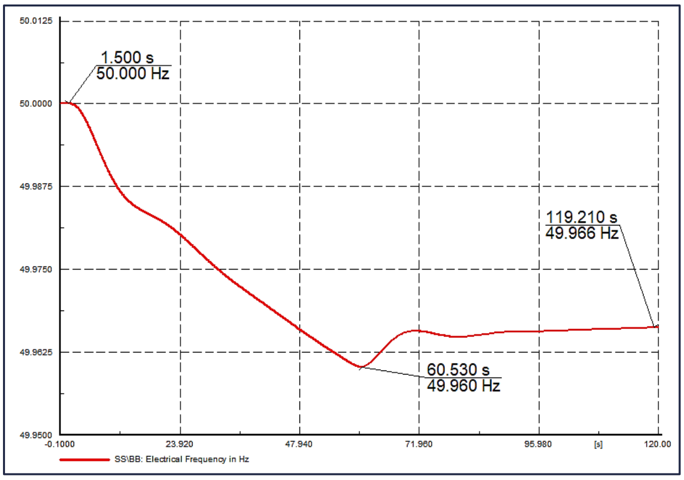

Figure 9: System Frequency (Hz) when the PV Power Plant loses 150 MW generation from 100% to 25% within 57 seconds

4. DISCUSSION

According to the findings from the load flow analysis, the simulation results reveal that interconnecting the 150 MW PV Power Plant into the X power system between the KS Substation and HI Substation will lead to a voltage rise in the area surrounding the interconnection point.

The load flow simulation results show that the voltage around the interconnection point, both before and after the integration of the 150 MW PV Power Plant, does not exceed the applicable limits of (+5%, -10%). Furthermore, there are no loading limits (100%) exceeded by the transmission lines and Interbus Transformers (IBT), both before and after the integration of the 150 MW PV Power Plant.

However, in line with the short-circuit analysis, the three-phase short-circuit current near the Switching Station (the interconnection point) undergoes a slight increase when the 150

MW PV Power Plant is integrated. However, the breaking capacity (Ib) of the PV Power Plant is 22.16 kA, while at the switching station it is 28.12 kA. Therefore, it is recommended to use circuit breakers (CB) with a capacity of 40 kA at both the PV Power Plant and the switching station.

In the transient stability study, simulation results for both considered events indicate that the power system can reach a new stable state (convergent), whether it is the sudden loss of 150 MW generation from the PV Power Plant or the gradual loss of 150 MW generation within 57 seconds due to decreased solar radiation due to cloud movement. Therefore, it shows that the power system is still able to maintain its stability even when there are sudden or gradual loss of 150 MW generation from the PV Power Plant.

Utilizing a higher PV power generation capacity through a low-power transmission line presents several practical challenges. In maintaining voltage stability becomes difficult when the line capacity is insufficient for the power generated, leading to fluctuations and potential damage to connected equipment. Additionally, power quality issues, such as harmonics and voltage fluctuations, can affect overall system stability. Thermal stability is another concern, with inadequate infrastructure risking overheating and line losses. This not only reduces the line's lifespan but can also lead to outages. Reliability issues arise due to frequent power outages during periods of high PV generation, impacting both businesses and residential consumers. Integrating energy storage and upgrading grid infrastructure are often necessary to mitigate these challenges, alongside regulatory compliance and permitting requirements. In addressing these issues, technical, financial, and regulatory measures are essential to ensure a stable, reliable, and high-quality power supply from PV systems.

On the other hand, due to its intermittent nature, multiple load follower power facilities situated in the vicinity of the interconnection point of the PV power plant should have the capacity to offset the intermittency of the PV power generation. Overcoming the challenges of utilizing a higher PV power generation capacity through a low-power transmission line requires a combination of solutions. Reactive power compensation devices, such as capacitors and inductors, can be deployed strategically to regulate voltage and prevent fluctuations. Energy storage systems, like batteries, play a crucial role in maintaining power quality and reliability by storing excess PV-generated power and ensuring a steady supply during periods of low generation. Upgrading the transmission line's capacity and conductor size addresses thermal stability concerns and reduces resistive losses, extending the line's lifespan. In an overall assessment, a comprehensive approach is essential. It involves a thorough evaluation of the existing infrastructure, its compatibility with increased PV capacity, and the strategic implementation of solutions like reactive power compensation, energy storage, and transmission line upgrades. Tailoring these solutions to the specific challenges and regulatory requirements of the system ensures a resilient and efficient power supply.

5. CONCLUSION

Based on the previously presented study for the 150 MW PV Power Plant interconnection to the X power system, the following conclusions can be drawn:

1. The simulation results for power flow analysis indicate that:
   a. The voltage around the point of interconnection, both before and after the interconnection of the 150 MW PV Power Plant, does not exceed the allowable limits of +5% and -10%.
   b. There are no loading limitations (100%) for the transmission lines and Interbus Transformers (IBT) either before or after the interconnection of the 150 MW PV Power Plant.
2. The short-circuit current around the Switching Station (point of interconnection) slightly increases with the interconnection of the 150 MW PV Power Plant. It is advised to implement circuit breakers (CB) with a 40-kA capacity for the switching station and the PV Power Plant.
3. The system is still able to maintain its stability even in cases of sudden loss or intermittent generation from the 150 MW PV Power Plant, whether due to sudden outages or decreased solar radiation.

The overall conclusion of the study indicates that it is possible to interconnect the 150 MW PV Power Plant to the 150 kV voltage-level system for the X-Power system without significantly compromising the system's stability, loading capacity, or voltage.

Conflicts of Interest: The authors declare no conflict of interest.

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