

Study of power and voltage delivery after successfully black-start

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Abstract

Efforts to maintain the continuity of electricity distribution to customers and reduce the amount of Energy Not Distributed (END) are to speed up the recovery process due to disturbances in the electricity distribution system, especially blackouts. The strategy to speed up recovery in a total blackout is to do a black-start on a generator unit with a black-start facility and send voltage to a larger generator unit. At the Grati-Paiton Substation, the generator that has black-start facilities is the Grati Gas Steam Power Plant (GSPP). The delivery of power and voltage from the Grati-Paiton substation is required after the Grati GSPP successfully black-start. Study optimal power flow simulation in distributing power and voltage using DigSILENT software. Based on the simulation results, several schemes are used to distribute power and voltage from the Grati-Paiton substation within the generator's Mvar. As a result, the voltage during the distribution process meets the criteria according to the Grid. The most optimal scheme is with the least number of stages, the production of Mvar, which is still safe for power generation, and the voltage at the end of the Paiton substation still meets the nominal voltage according to the Grid.

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Keywords:

Black-start;
DigSILENT;
Grati-Paiton substation;

Article History:

Received: January 24, 2022

Revised: May 25, 2022

Accepted: May 29, 2022

Published: October 8, 2022

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INTRODUCTION

Electrical energy is an absolute requirement that must be met because almost all activities, such as public, business, industrial, social, and household require electrical energy to maintain activities in these fields. Therefore, maintaining the continuity of electricity distribution to customers is very important and is a responsibility carried out by Perusahaan Listrik Negara (PLN) or State Electricity Company to meet the needs of electrical energy in Indonesia. One of the efforts to maintain the continuity of electricity distribution is to accelerate the recovery process when a disturbance occurs in the distribution system to reduce the negative impact on society, the economy, and the electricity system.

Disturbances in an electric power grid system are total outages or blackouts. A

blackout is a total loss of electrical power, resulting in the blackout of all loads on the electrical system. Several cases of total outages or blackout disturbances have occurred: [1, 2, 3]

1. September 28, 2003, in Italia and Swiss
2. August 18, 2005, in Java Bali - Indonesia
3. November 10–20, 2009, in Brazil and Paraguay
4. July 30 – 31, 2012, in India.
5. November 1, 2014, in Bangladesh.
6. January 26, 2015, in Pakistan.
7. March 31, 2015, in Turkey.
8. March 13, 2016, in Sri Lanka.
9. June 2019 in Argentina, Paraguay, and Uruguay.
10. August 4–5, 2019, in West Java, Indonesia.

Several recovery strategies are carried out when a blackout occurs. One of them is that in most blackout cases, a power grid can be

recovered with the help of another power grid system that is still operating [4]. However, when an electrical blackout occurs and does not have a network that is connected to other electricity networks. For this reason, external generators are needed to revive parts of the power system to recover from blackouts (black-start). Black-starts are generally small units that will not be able to recover most of the lost load but are used to supply power and voltage to power plants experiencing blackouts [1].

Black-start power source selection usually, black-start power sources include units with self-start ability, such as Hydroelectric Power Plant (HPP) units, fuel, gas turbine units, and support power provided by adjacent interconnected systems. In addition, gas-turbine-based plants can be profitably used in power system restoration. In general, HPP stations are designated as black-start sources for powering the Grid because HPP requires little energy to start operation. Therefore, they are most commonly used as black-start sources.

Another method used for black-start sources is VSC-HVDC [5-7]. However, this limitation of VSC-HVDC requires a system cost at the time of black-start. Also, the latest method with microgrids that can self-start during black-start [8-9] utilizes renewable energy such as biodiesel, solar, wind [10-13], and battery systems [14][15]. Still, microgrids have limitations in terms of capacity and stability.

The 150 kV Grati Substation (SS) – Paiton Substation (SS), as part of the Java Madura Bali 500kV Interconnection System, has a generating unit with black-start facilities. It is HPP, namely HPP Sutami. In the event of a blackout at the Grati SS – Paiton SS 150kV, the HPP Sutami will send voltage and power to the Grati SS. So that the generation unit in Grati can be generated and continued by sending voltage to the Paiton SS, to provide voltage and power to the generating unit which is in Paiton SS [16]. The main purpose of the black-start at the HPP Sutami is the delivery of voltage and power to the Paiton SS because, at the Paiton SS, there is the largest generation complex in the 150kV Grati SS-Paiton SS and the Java Madura Bali Electricity System.

The process of sending voltage and power from Sutami HPP to the Grati SS and Paiton SS has several obstacles, as shown in Figure 1. The biggest obstacle is the distance of the voltage delivery from the Sutami HPP to the Grati SS and Paiton SS.

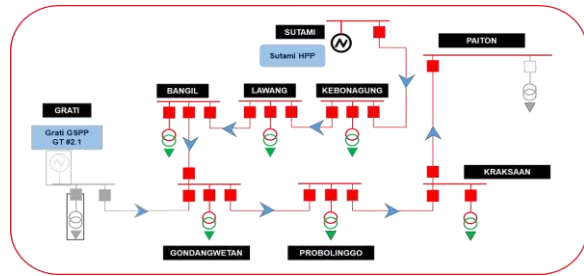


Figure 1. Black-start Grati SS – Paiton SS from Sutami HPP

The voltage is sent via the High Voltage Air Line (HVAL) with a line length of 129.3 Km, passing through Sutami SS – Kebonagung SS – Lawang SS – Bangil SS – Gondangwetan SS – Grati SS.

After the Grati Gas Steam Power Plant (GSPP) can be generated, it is continued by sending voltage to the Paiton SS via SUTT with a line length of 104.9 Km, passing through the Grati SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS. However, the long-distance of this voltage delivery results in a large charging line and affects the stability of the generating unit at the Sutami HPP because it makes it difficult to regulate the Mvar of the generating. In addition, it also causes the recovery period to become longer so the duration of the outage is also getting longer, and the Energy Not Distributed (END) is also getting bigger.

This obstacle was seen during the black-start test using the Dispatcher Training Simulator (DTS). Testing and sending voltage to Grati and Paiton takes 3 hours until the Grati GSPP can be generated. Likewise, the black-start testing and line charging on the Sutami hydropower plant. The trial was carried out with a black-start of 2 units of Sutami HPP, and a no-load charging line up to the Bangil SS. In this trial, it was observed that the Mvar of units 1 and 2 of the Sutami hydropower plant reached -18 Mvar and the voltage at the Bangil SS reached 158kV, with a test duration of 29 minutes (from the target below 15 minutes).

The black-start method using the Sutami HPP cannot be used. Other black-start methods include using a diesel generator, gas turbine, compressed air storage, etc. These methods have different approaches and depend on several factors, such as cost, complexity, availability of energy sources, interconnectivity with other generating networks, and how fast the method can generate electricity.

To overcome these obstacles, the researchers installed black-start facilities in the Grati GSPP Units Block 1 and Block 2 using

Diesel Power Plant (DPP) with High-Speed Diesel (HSD) fuel. Installing a black-start facility at the Grati GSPP will speed up the voltage and power delivery to the generating at the Paiton SS. It will speed up the fault recovery process and reduce outage duration, which means that END can be reduced or minimized. Planning the power delivery scenario needs to consider several things, such as the voltage delivery line's selection, the delivery line's length, and the power flow calculation.

A strategy for sending power and voltage from Grati SS to Paiton SS is needed after the Grati GSPP successfully black-start. Distribution of power and voltage through the 500kV Grati – Paiton transmission line is not possible, because the Mvar of the generator exceeds the maximum absorption limit, and the voltage in Paiton is below the allowable nominal voltage. Several methods can be used for optimal power flow, namely [17] are classified into two categories: Conventional methods and Artificial Intelligence-based methods. The conventional methods are subdivided into the following: Linear Programming, Gradient methods, Quadratic Programming, Newton-Raphson, Nonlinear Programming, and Interior Point. This method has drawbacks, including only getting one optimized solution each time the simulation runs, and the process is slow because this method is deterministic. The artificial intelligence methods are subdivided into the following: Genetic algorithm, Particle swarm, Artificial Neural Network, Bee colony optimization, Differential evolution, Grey wolf optimizer, and Shuffled frog-leaping. This method is suitable for solving multi-objective optimization problems. The Artificial Intelligence methods use Matlab software [8][18]. Optimal Power Flow can be done using the ETAP Power Station software [19][20]. Both of these software has limitations compared to DigSILENT software. The usability comparison between DigSILENT and Matlab/Etab software [21] is shown in Table 1.

In this discussion, the author conducts a power flow study for eight power and voltage delivery cases from the Grati SS to the Paiton SS to determine the most optimal voltage delivery path. Black-start fault recovery testing cannot be done directly but with an approach through simulation using [software [1]. So in this plan, using an approach through simulation with DigSILENT software.

Table 1. The usability comparison between DigSILENT and Matlab/Etab software

No.	Usability	Dig SILENT	Matlab/Etab
1	Requires Single line System Diagram	√	√
2	Requires Data Generator, Transformer, Bus, transmission	√	√
3	Need to Determine the Swing Generator	√	√
4	Load Flow Analysis	√	√
5	Interactive online to the SCADA system	√	X
6	Short Circuit Calculation	√	X
7	Harmonic Analysis	√	√
8	Protection Coordination	√	√
9	Stability Calculation	√	X
10	Modal analysis	√	X
11	Unlimited Bus and real system	√	X
12	For Industry	√	X

METHODS

Data

The Grati - Paiton SS is part of the Java Bali Electrical Interconnection Network System [22, 23, 24]. The Grati - Paiton SS 150kV serves the power needs of the Malang, Bangil area. Malang, Pasuruan, Probolinggo, Jember, Banyuwangi to Bali via the Banyuwangi – Gilimanuk 1,2,3,4 Sea Cable line according to the network shown in Figure 2.

The Grati - Paiton SS 150kV has a source of 2540 MW with a daytime peak load of 1513 MW and a night peak load of 1748 MW. Table 2 shows the source for the Grati - Paiton SS 150kV. In the Grati - Paiton SS 150kV, in addition to the 150kV generator, there is also a 500kV generator as the main power source for the Java-Bali electricity interconnection network from the East. Table 3 shows the 500kV generation located in the Grati - Paiton SS.

When the Java-Bali Electricity Interconnection Network experienced a blackout, the system started with the black-start process of generating a black-start facility. One of the power plants that have black-start facilities is the Grati GSPP, at Block 1 (500kV) or Block 2 (150kV) GSPP, which will send power to the generation at Paiton

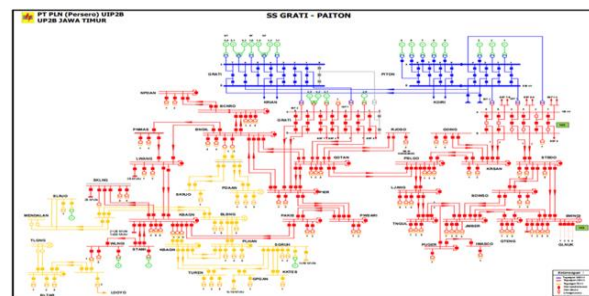


Figure 2. Grati - Paiton SS 150kV

Table 2. 150kV Power at Grati – Paiton SS

No	Substation (SS)	Source	Supply Power (MW)
1	Paiton SS	IBT-1 500 kV – 500 MVA	385
2	Paiton SS	IBT-1 500 kV – 500 MVA	385
3	Paiton SS	IBT-1 500 kV – 500 MVA	385
4	Grati SS	IBT-1 500 kV – 500 MVA	385
5	Grati SS	IBT-1 500 kV – 500 MVA	385
6	Grati SS	Grati GSPP Block 2	450
7	Sutami SS	Sutami HPP (3 units)	105
8	Wlingi SS	Wlingi HPP (2 units)	40
9	Sengguruh SS	Sengguruh HPP (2 units)	20
Total			2540

IBT = Inter Bus Transformer

Table 3. 500kV generation at Grati - Paiton SS 150kV

No	Substation (SS)	Generator Type	Installed Power (MW)	DMN (MW)
1	Grati EHVS	Grati GSPP 1.1	100.8	100.25
2	Grati EHVS	Grati GSPP 1.2	100.8	100.25
3	Grati EHVS	Grati GSPP 1.3	100.8	100.25
4	Grati EHVS	Grati GSPP 1.0	159.6	155.48
5	Grati EHVS	Grati GSPP 3.1	156.17	145
6	Grati EHVS	Grati GSPP 3.2	158.94	145
7	Grati EHVS	Grati GSPP 3.0	165	165
8	Paiton EHVS	ESPP #1	400	370
9	Paiton EHVS	ESPP #2	400	370
10	Paiton EHVS	ESPP #3	830	813
11	Paiton EHVS	ESPP #5	615	610
12	Paiton EHVS	ESPP #6	615	610
13	Paiton EHVS	ESPP #7	615	610
14	Paiton EHVS	ESPP #8	615	610

Further, build the Java Bali Electricity System from the Eastside after the generation at Paiton ESPP has been successfully operated again.

After the Grati GSPP either block 1 or 2, successfully black-starts, it is necessary to conduct a power flow study to send the power and voltage from the Grati SS to the Paiton SS, to obtain the most optimal power delivery path and loading. So that it is fast and safe when the power and voltage reach the Paiton SS and the generation at Paiton EHVS can immediately be operated to restore the electricity system in Java - Bali.

Table 4 is the data for several Extra High Voltage Air Line (EHVAL) and High Voltage Air Line (HVAL) segments on the Grati - Paiton SS. The data can be used as a power delivery line from the Grati SS to Paiton SS, and the transformation data can be installed on each SS on the line.

Research Methodology

The installation of the black-start facility on the Grati GSPP Block 1 and 2 requires the design of a power and voltage delivery line scheme from the Grati SS to the Paiton SS.

Table 4. Generating of 500kV in 150kV Grati - Paiton SS

No	CONDUCTOR		CONDUCTOR DATA		
	From	To	Voltage (kV)	Distance (km)	Nominal Current (A)
1	Grati	Paiton	500	87.87	2551
2	Grati	Pier	150	32.90	3104
3	Grati	Gondangwetan	150	21.07	1620
4	Pier	Bangil	150	5.15	1620
5	Bangil	Gondangwetan	150	16.81	630
6	Gondangwetan	Probolinggo	150	33.83	630
7	Probolinggo	Kraksaan	150	30.24	1190
8	Kraksaan	Paiton	150	19.78	1190

After the Grati GSPP Block 1 or 2 successfully black-starts, the power from the generator will be sent to the Paiton SS, to send power and voltage to the generating at Paiton EHVAL so that it can immediately be operated to restore the system that experienced a blackout.

Power delivery from the Grati SS to the Paiton SS can be done with several schemes and all possible schemes will be simulated using DigSILENT to get the most optimal scheme. Figure 3 until Figure 10 are some schemes that send power and voltage from the Grati SS to the Paiton SS after the Grati GSPP successfully black-start.

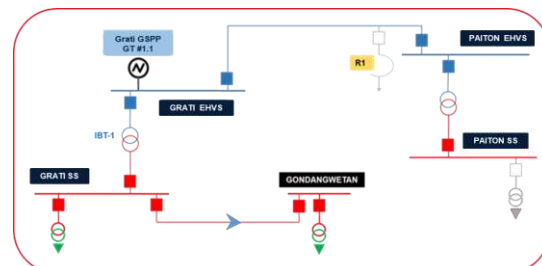


Figure 3. Power and Voltage Delivery Lines in Schematic 1

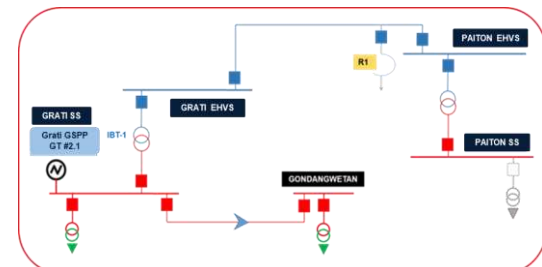


Figure 4. Power and Voltage Delivery Lines in Schematic 2

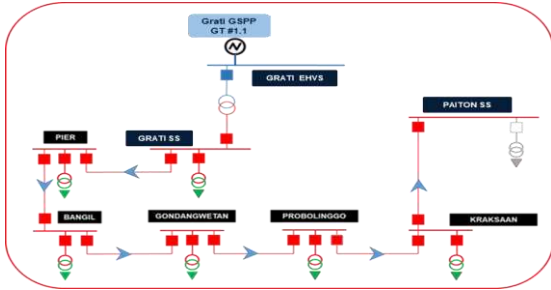


Figure 5. Power and Voltage Delivery Lines in Schematic 3

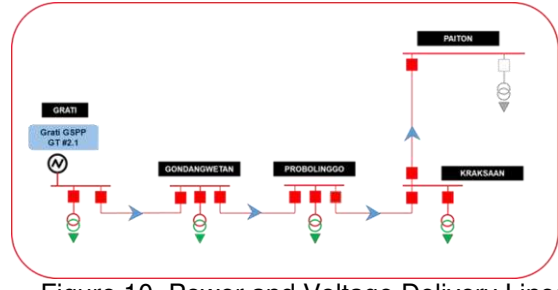


Figure 10. Power and Voltage Delivery Lines in Schematic 8

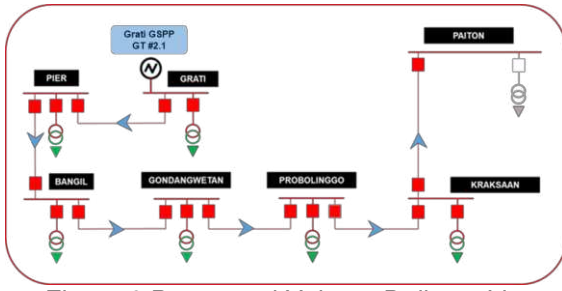


Figure 6 Power and Voltage Delivery Lines in Schematic 4

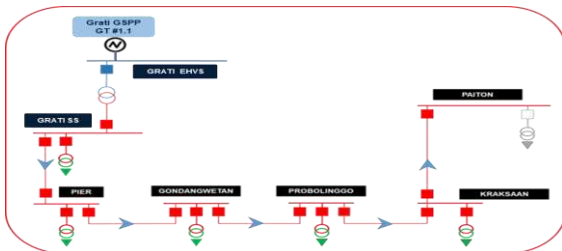


Figure 7. Power and Voltage Delivery Lines in Schematic 5

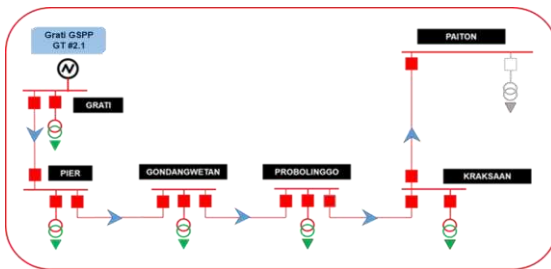


Figure 8. Power and Voltage Delivery Lines in Schematic 6

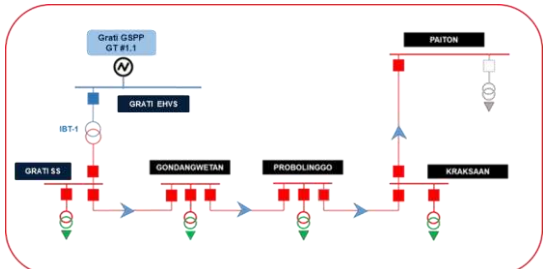


Figure 9. Power and Voltage Delivery Lines in Schematic 7

DigSILENT software can be used to plan all possible models of the most optimal power and voltage delivery so that it can be used as the main strategy for recovery from blackouts. The steps for modeling and simulating the power and voltage delivery scheme can be seen in the flowchart in Figure 11. The initial step of modeling and simulating power and voltage delivery schemes in this research start by activating the Java Bali electricity network database on the DigSILENT application.

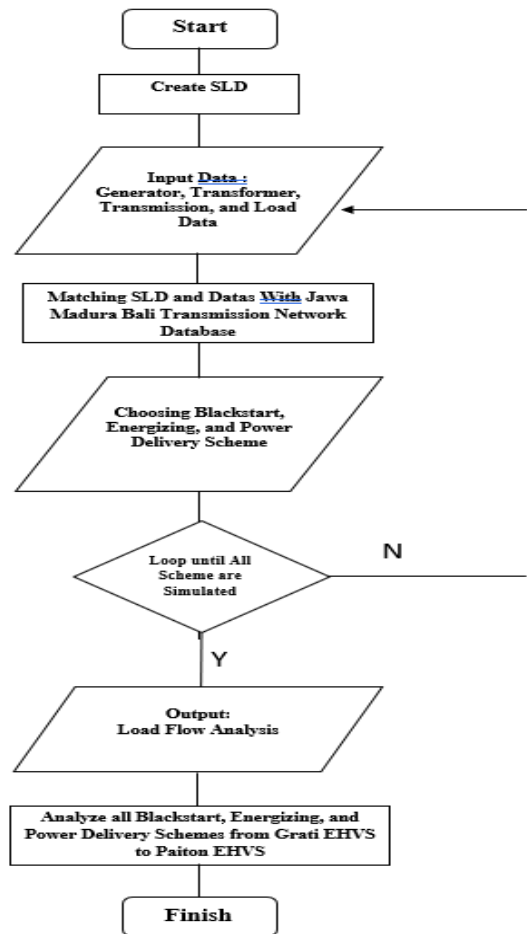


Figure 11. Flowchart of Schematic Modeling on DigSILENT

To make a case study of the power and voltage delivery scheme, preliminary planning data such as the location of the generator, the power and voltage delivery lines, and the transformer load on the recovery line must first be prepared. Following are the steps in modeling DigSILENT.

1. Activating the Java Bali electricity network database. Figure 12 shows the database stored in the DigSILENT application that can be activated for simulation

2. Create Single Line Diagram (SLD) for all power and voltage delivery schemes from Grati to Paiton. Figure 13 shows the SLD in the DigSILENT application that will be used for the simulation

3. Make a model for each of the power and voltage delivery schemes. Figure 14. shows the modeling of the power and voltage delivery scheme in the DigSILENT application that will be used for the simulation

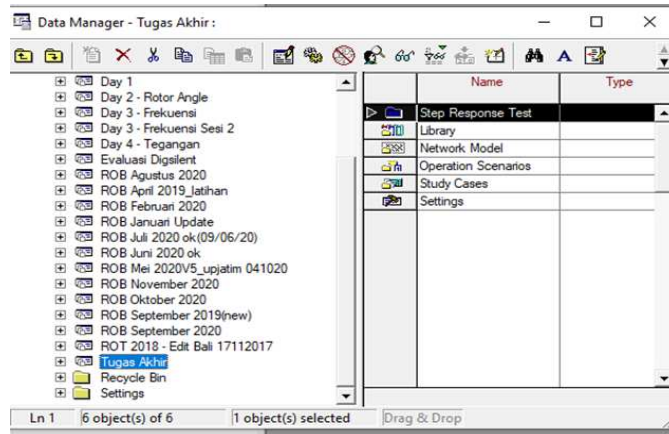


Figure 12. Database on DigSILENT

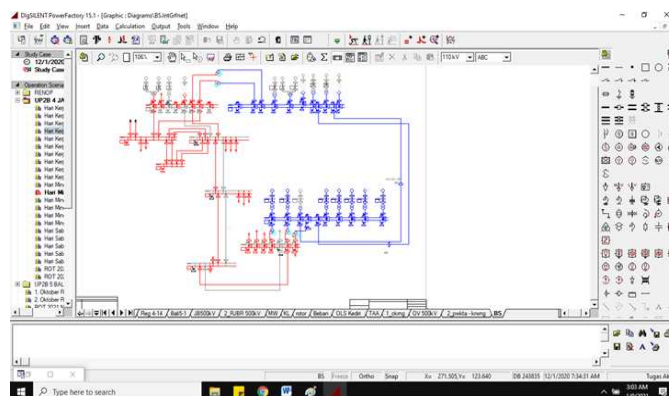


Figure 13. SLD modeling on DigSILENT

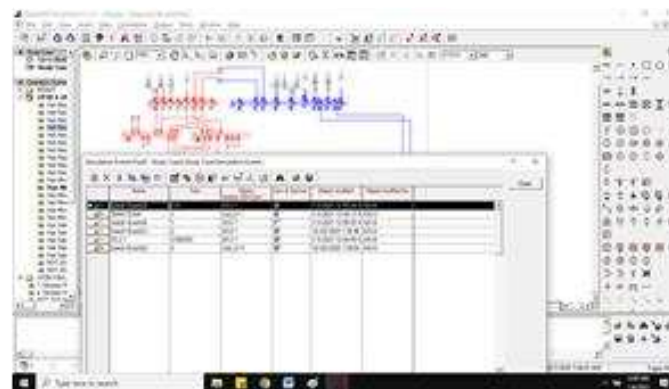


Figure 14. Schematic drawing of power and voltage delivery on DigSILENT

RESULTS AND DISCUSSION

Simulation of Power and Voltage Delivery on Schematic 1

In this scheme, after the Grati GSPP GT#1.1 generator black-start, power and voltage will be sent from Grati to Paiton via 500kV transmission. Before the power and voltage are sent via 500kV transmission, the generator is given a transformer load of 30MW (Transformers on Grati SS and Gondangwetan SS) according to the minimum load of the generator.

Once the minimum generator load is reached, the 500kV Grati – Paiton conductor is operated for power and voltage delivery. The stages in scheme 1 are shown in Table 5. The magnitude of the Mvar of the Grati GT#1.1 GSPP Generator and the Voltage on the Network during the sending power and voltage are shown in Figure 15.

The simulation results of scheme 1, Stages 1-2 in Table 4, after the Grati GSPP GT#1.1 black-start, and fill the voltage at the 500kV Grati EHVS, the generator produces 4.5 Mvar, and the voltage at the Grati EHVS is 503.39 kV in Figure 15. To load the generator, the Grati IBT-1 is operated to provide voltage to 150kV Grati SS in stage 3. The generator produces 4.2 Mvar, the voltage at Grati is 488.73 kV and 151.7 kV in Figure 15. When the voltage reaches Gondangwetan SS, the load on Grati transformer-1 and Gondangwetan transformer-1 is 30MW, the generator produces 12.4 Mvar and the voltage at Grati is 485.42 kV and 150.33 kV (voltage at Gondangwetan SS is 149.94 kV).

Table 5. Stages in Scheme 1

No	Stages	Description
1	Grati GSPP GT#1.1	Black-start
2	Busbar 500kV Grati	500kV Grati EHVS Voltage
3	Grati IBT-1	SS 150kV Grati Voltage Grati distribution
4	Grati transformer-1	transformer operation with a load of 5 MW
5	150kV Grati – Gondangwetan Conductor	SS 150kV Gondangwetan Voltage
6	Gondangwetan transformer -1	Gondangwetan distribution transformer operation with a load of 25 MW
7	500kV Grati – Paiton conductor	Conductor enter, voltage up to EHVS 500 kV Paiton IBT-1 enter, voltage to 150kV Paiton SS to send power to the SST generator in Paiton
8	Paiton IBT-1	

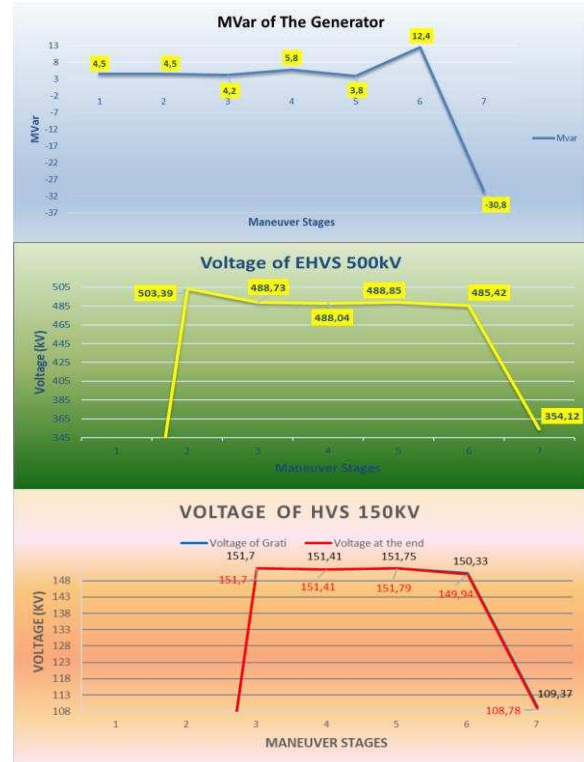


Figure 15. Mvar of Generating and Voltage on Schematic 1

When the 500kV Grati–Paiton conductor is operated to send voltage to the Paiton EHVS, the Grati Generator absorbs Mvar up to -30.8 (Grati Generator is capable of absorbing a maximum Mvar of 30.8 Mvar). But the voltage at Grati is 354.12 kV and 109.37 kV, below the limit minimum voltage 500kV (475 kV according to Network Rules) and 150 kV (135kV according to Network Rules). Because at stage 7 the 500kV voltage limit was not reached, it cannot be continued until stage 8, namely sending voltage to the Paiton SS 150kV via Paiton IBT-1 to provide SST power for the Paiton ESPP.

Simulation of Power and Voltage Delivery on Schematic 2

In this scheme, after the black-start Grati GT#2.1 GSPP generator, the generator is given a load from the distribution transformer of 30MW according to the minimum load declared by the generator. The stages in Scheme 2 are shown in Table 6 and the magnitude of the Mvar of the Grati GT#2.1 of the GSPP Generator. The Voltage on the Network during the process of sending power and voltage are shown in Figure 16. Based on the simulation results of schema 2, in Table 5, after the GSPP Grati GT#2.1 black-start, and filling the voltage at the 150kV Grati SS, the generator produces 0 Mvar.

Table 6. Stages in Scheme 2.

No	Stages	Description
1	Grati GSPP GT#2.1	Black-start,
2	Busbar 150kV Grati	150kV Grati SS Voltage
3	Grati transformer-1	The Grati distribution transformer operates with a load of 5 MW
4	150kV Grati – Gondangwetan Conductor	150kV Gondangwetan SS Voltage
5	Gondangwetan transformer-1	The Gondangwetan distribution transformer operates with a load of 25 MW
6	Grati IBT-1	500kV Grati EHVS voltage
7	500kV Grati - Paiton conductor	Introductory entry, voltage up to 500 kV Paiton EHVS
8	Paiton IBT-1	IBT-1 enter, voltage to 150kV Paiton SS to give power to the SST generator in Paiton

voltage at Grati is 348.93 kV and 105.52 kV, below the minimum voltage limit of 500kV and 150 kV. In this scheme 2, because in the 7th stage the 500kV voltage limit was not reached, it cannot be continued until the 8th stage, namely sending voltage to the Paiton SS 150kV via Paiton IBT-1 to provide SST power for the Paiton ESPP.

Simulation of Power and Voltage Delivery on Schematic 3

In this scheme, after the Grati GT#1.1 GSPP generator black-start, Grati IBT-1 operated to send power and voltage to Paiton via 150kV transmission. Power delivery is carried out in stages through Grati SS – Pier SS – Bangil SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS.

The stages in Scheme 3 are shown in Table 7 and the magnitude of the Mvar of the Grati GT#1.1 of the GSPP Generator. The voltage on the network during the process of sending power and the voltage are shown in Figure 17. Based on the simulation results of schematic 3, after the Grati GT#1.1 GSPP black-start, and filling the voltage at the 500kV Grati EHVS, the generator produces 4.5 Mvar, and the voltage at the Grati EHVS is 503.39 kV.

To load the generator, the Grati IBT-1 is operated to provide a voltage to the 150kV Grati SS, the generator produces 4.2 Mvar, and the voltage at Grati is 488.73 kV and 151.7 kV. The generator is given a minimum load through Grati transformer-1, Pier transformer-1, and Bangil transformer-1. At this stage, the generator produces 12.4 Mvar, and the voltages are 485.4 kV and 149.25 kV, respectively.

The process of sending power and voltage to the Grati SS begins with operating the Grati – Pier conductor, followed by the Pier – Bangil conductor, Bangil – Gondangwetan conductor, Gondangwetan – Probolinggo conductor, Probolinggo – Kraksaan conductor, Kraksaan – Paiton conductor. From the simulation results, and obtained data for all stages, the generator produces Mvar of 3.7 Mvar - 12.4 Mvar, and the voltage on the 500 kV side is 485.02 kV - 503.39 kV, and on the 150kV side (end side) is 148, 3 kV – 151.87 kV.

The voltage delivery from Grati to Paiton was successfully carried out, and when it arrived at the Paiton SS was 148.96 kV, then it could be continued to operate the SST of the ESPP Paiton Generator so that the generator was immediately operated for the system recovery.

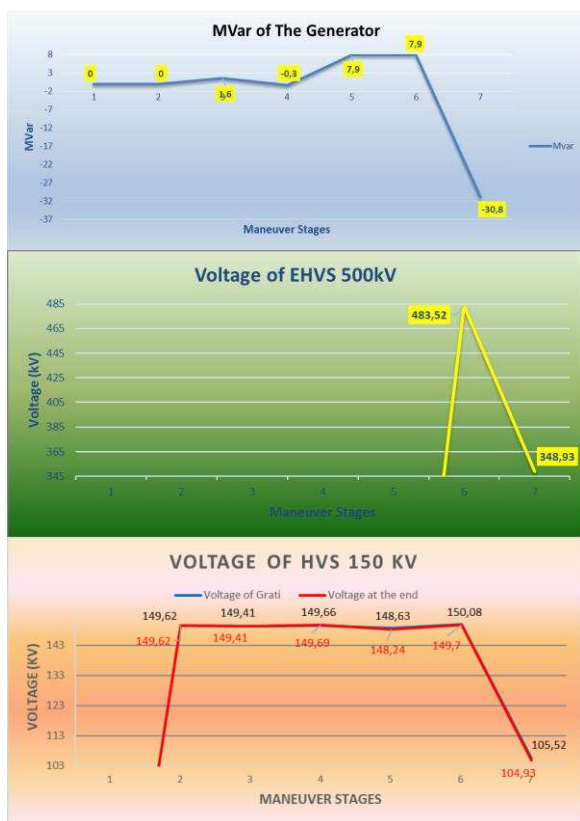


Figure 16. Mvar of Generating and Voltage on Schematic 2

The generator is given a minimum load through Grati transformer-1 and Gondangwetan transformer-1. At this stage, the generator produces 7.9 Mvar, and the observed voltage is 148.63 kV in Figure 16. To send voltage through the 500kV Grati – Paiton conductor, the Grati IBT-1 is operated, the 500kV voltage is 483.52 kV. When the 500kV Grati – Paiton conductor is operated to send voltage to the Paiton EHVS, the Grati Generator absorbs -30.8 Mvar, but the

Table 7. Stages in Scheme 3

No	Stages	Description
1	GSPP GT#1.1	Black-start
2	Busbar 500kV Grati	500kV Grati EHVS voltage
3	Grati IBT-1	150kV Grati SS Voltage
4	Grati transformer-1	The grati distribution transformer operates with a load of 5 MW
5	150kV Grati – Pier Conductor	150kV Pier SS Voltage
6	Pier transformer -1	The pier distribution transformer operates with a load of 5 MW
7	150kV Pier – Bangil conductor	150kV Bangil SS voltage
8	Bangil transformer -1	Bangil distribution transformer operating with a load of 20 MW
9	150kV Bangil – Gondangwetan conductor	150kV Gondangwetan SS Voltage
10	Gondangwetan transformer-1	Gondangwetan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar Generating Grati)
11	150kV Gondangwetan – Probolinggo conductor	150kV Probolinggo SS Voltage
12	Probolinggo transformer -1	Probolinggo distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar Generating Grati)
13	150kV Probolinggo – Kraksaan conductor	150kV Kraksaan SS Voltage
14	Kraksaan transformer -1	Kraksaan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar Grati generator)
15	150kV Kraksaan – Paiton conductor	voltage to 150kV Paiton SS to send power to the SST generator in Paiton

Simulation of Power and Delivery on Schematic 4

In this scheme, after the black-start Grati GT#2.1 GSPP Generator, power and voltage are sent to Paiton via 150kV transmission in stages via Grati SS – Pier SS – Bangil SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS. The stages in Scheme 4 are shown in Table 8 The magnitude of the Mvar of the Grati GT#2.1 GSPP Generator and the Voltage on the Network during the sending power and voltage are shown in Figure 18.

The simulation results of schematic 4, after Grati GT#2.1 GSPP black-start, and charging voltage at the 150kV Grati SS, resulted in 0 Mvar. The generator is given a minimal load through Grati transformer-1, Pier transformer-1, and Bangil transformer-1. At this stage, the generator produces 8 Mvar, and the voltage is 147.54 kV in Figure 18.

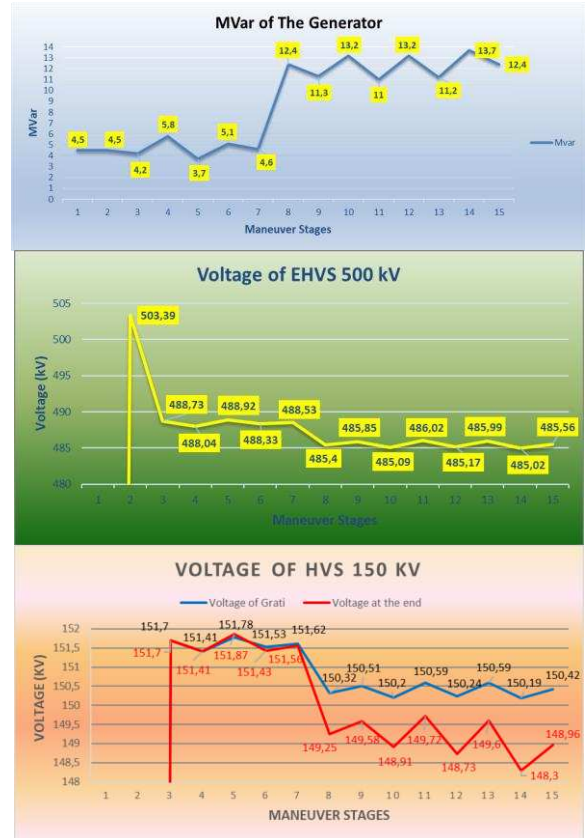


Figure 17. Mvar of Generating and Voltage on Schematic 3

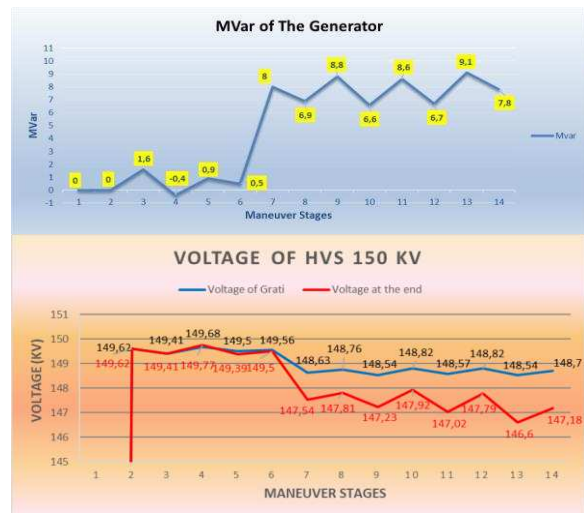


Figure 18. Mvar of Generating and Voltage on Schematic 4

From the simulation results, obtained data for all stages, the generator produces -0.4 Mvar – 9.1 Mvar, and a voltage of 150kV (end side) obtained data of 146.6 kV – 149.77 kV.

Table 8. Stages in Scheme 4

No	Stages	Description
1	GSPP GT#2.1	Black-start
2	Busbar of 150kV Grati	150kV Grati SS voltage
3	Grati transformer -1	Grati distribution transformer operating with a load of 20 MW
4	150kV Grati - Pier conductor	150kV Pier SS voltage
5	Pier transformer-1	Pier distribution transformer operating with a load of 20 MW
6	150kV Pier - Bangil conductor	150kV Bangil SS voltage
7	Bangil transformer-1	Bangil distribution transformer operating with a load of 20 MW
8	150kV Bangil - Gondangwetan conductor	150kV Gondangwetan SS voltage
9	Gondangwetan transformer -1	Gondangwetan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati generator)
10	150kV Gondangwetan - Probolinggo conductor	150kV Probolinggo SS Voltage
11	Probolinggo transformer -1	Probolinggo distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati generating)
12	150kV Probolinggo - Kraksaan conductor	150kV Kraksaan SS voltage
13	Kraksaan transformer -1	Kraksaan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati generating)
14	150kV Kraksaan - Paiton conductor	voltage up to 150kV Paiton SS to send power to the SST generator in Paiton

The voltage delivery from Grati to Paiton was successfully carried out, and when it arrived at the Paiton SS was 147.18 kV, then it could be continued to operate the SST of the Paiton ESPP Generator so that the generator was immediately operated for the system recovery.

The process of sending power and voltage to the Grati SS begins with operating the Grati - Pier conductor, followed by the Pier - Bangil conductor, Bangil - Gondangwetan conductor, Gondangwetan - Probolinggo conductor, Probolinggo - Kraksaan conductor, Kraksaan - Paiton conductor.

Simulation of Power and Voltage Delivery on Schematic 5

In this scheme, after the Grati GT#1.1 GSPP generator black-start, Grati IBT-1 operated to send power and voltage to Paiton via 150kV transmission. Power delivery is carried out in

stages through Grati SS – Pier SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS. The stages in scheme 5 are shown in Table 9. The magnitude of the Mvar of the Grati GT#1.1 GSPP Generator and the Voltage on the Network during the process of sending power and voltage are shown in Figure 19.

Based on the simulation results of schematic 5, after the Grati GT#1.1 GSPP black-start, and fills the voltage at the Grati EHVS 500kV, the generator produces 4.5 Mvar, and the voltage at the Grati EHVS is 503.39 kV.

The Grati IBT-1 is operated to provide voltage to the 150kV Grati SS to provide a generator load. When Grati IBT-1 enters, the generator produces 4.2 Mvar, the voltage at Grati is 488.73 kV and 151.7 kV in Figure 19. The generator is given a minimum load through Grati transformer-1, Pier transformer-1, and Gondangwetan transformer-1.

At this stage, the generator produces 11.7 Mvar, the voltages are 485.68 kV and 149.34 kV.

Table 9. Stages in Scheme 5

No	Stages	Description
1	GSPP GT#1.1	Black-start
2	Busbar of 500kV Grati	500kV Grati EHVS voltage
3	Grati IBT-1	150kV Grati SS voltage
4	Grati transformer-1	Grati distribution transformer operating with a load of 5 MW
5	150kV Grati - Pier conductor	150kV Pier SS voltage
6	Pier transformer-1	The pier distribution transformer operates with a load of 5 MW
7	150kV Pier - Gondangwetan conductor	150kV Gondangwetan SS voltage
8	Gondangwetan transformer-1	Gondangwetan distribution transformer operating with a load of 20 MW
9	150kV Gondangwetan - Probolinggo conductor	150kV Probolinggo SS voltage
10	Probolinggo transformer-1	Probolinggo distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
11	150kV Probolinggo - Kraksaan conductor	150kV Kraksaan SS voltage
12	Kraksaan transformer -1	Kraksaan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
13	150kV Kraksaan - Paiton conductor	voltage up to 150kV Paiton SS to send power to the SST generator in Paiton

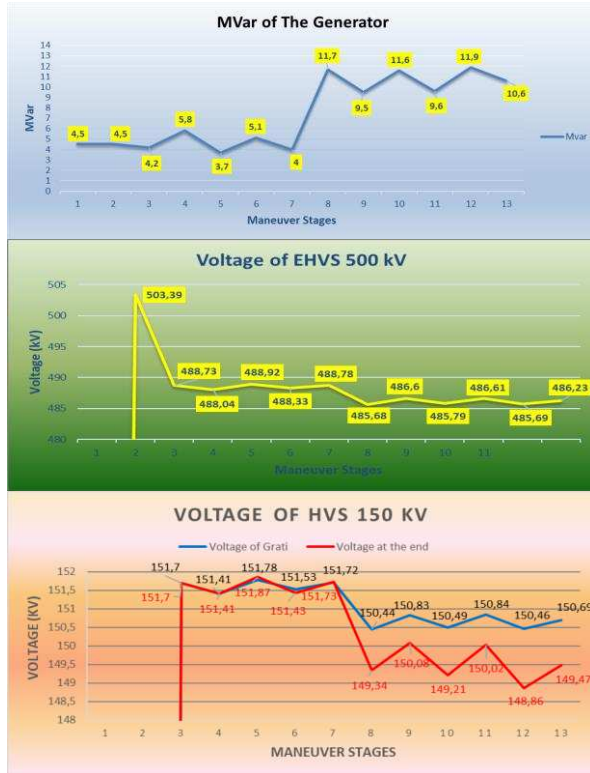


Figure 19. Mvar of Generating and Voltage on Schematic 5

The process of sending power and voltage to the Grati SS begins with operating the Grati – Pier conductor, followed by the Pier–Gondangwetan conductor, the Gondangwetan–Probolinggo conductor, the Probolinggo–Kraksaan conductor, and the Kraksaan–Paiton conductor. Then, for each SS, a distribution transformer is given to meet the generator's minimum loading and maintain the grid voltage and Mvar of the generator.

From the simulation results, the data obtained for all stages, the generator produces 3.7 Mvar - 11.9 Mvar, the side voltage of 500 kV gets data of 485.69 kV - 503.39 kV, and on the 150kV side (end side) data is obtained 148.86 kV – 151.87 kV.

The voltage delivery from Grati to Paiton was successfully carried out, and the voltage when it arrived at the Paiton SS was 149.47 kV, then it could be continued to operate the SST of the Paiton ESPP so that the generator was immediately operated for system recovery.

Simulation of Power and Voltage Delivery on Schematic 6

In this scheme, after the Grati GT#2.1 GSPP generator black-start, power and voltage are sent to Paiton via 150kV transmission in stages via Grati SS – Pier SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS. The stages in scheme 6 are shown in Table 10.

The magnitude of the Mvar of the Grati GT#2.1 GSPP generator and the connection to the network during the power and voltage delivery process are shown in Figure 20.

Based on the simulation results of schematic 6, after the Grati GT#2.1 GSPP black-start, and filling the voltage at the 150kV Grati SS, the generator produces 0 Mvar. Then, the generator is given a minimum load through Grati transformer-1, Pier transformer-1, and Gondangwetan transformer-1. At this stage, the generator produces 7.3 Mvar and 147.6 kV in Figure 20.

Table 10. Stages in Scheme 6

No	Stages	Description
1	GSPP GT#2.1	Black-start
2	Busbar of 150kV Grati	150kV Grati SS voltage
3	Grati transformer-1	Grati distribution transformer operating with a load of 5 MW
4	150kV Grati – Pier conductor	150kV Pier SS voltage
5	Pier transformer -1	Pier distribution transformer operating with a load of 5 MW
6	150kV Pier-Gondangwetan conductor	150kV Gondangwetan SS voltage
7	Gondangwetan transformer -1	Gondangwetan distribution transformer operating with a load of 20 MW
8	150kV Gondangwetan - Probolinggo conductor	150kV Probolinggo SS voltage
9	Probolinggo transformer -1	Probolinggo distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
10	150kV Probolinggo - Kraksaan conductor	150kV Kraksaan SS voltage
11	Kraksaan transformer -1	Kraksaan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
12	150kV Kraksaan - Paiton conductor	Voltage up to 150kV Paiton SS to send power to the SST generator in Paiton

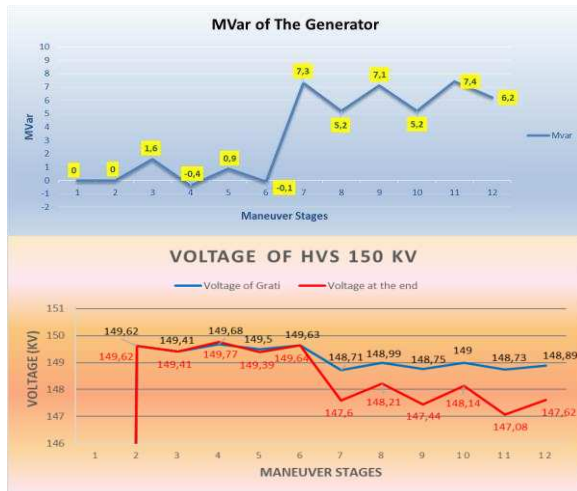


Figure 20. Mvar of Generating and Voltage on Schematic 6

The process of sending power and voltage to the Grati SS begins with operating the Grati – Pier conductor, followed by the Pier-Gondangwetan conductor, the Gondangwetan-Probolinggo conductor, the Probolinggo-Kraksaan conductor, and the Kraksaan-Paiton conductor. For each SS with voltage, 1 distribution transformer is given to meet the generator's minimum loading and maintain the grid voltage and Mvar of the generator.

From the simulation results, obtained data for all stages, the generator produces -0.4 Mvar – 7.4 Mvar, and a voltage of 150kV (end side) obtained data of 147.08 kV – 149.77 kV. The voltage delivery from Grati to Paiton was successfully carried out, and the voltage when it arrived at the Paiton SS was 147.62 kV, then it could be continued to operate the SST of the Paiton ESPP Generator so that the generator was immediately operated for the system recovery.

Simulation of Power and Voltage Delivery on Schematic 7

In this scheme, after the Grati GT#1.1 GSPP generator black-start, power and voltage are sent to Paiton via 150kV transmission in stages via Grati SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS. The stages in Scheme 7 are shown in Table 11.

The magnitude of the Mvar of the Grati GT#1.1 GSPP generator and the connection to the network during the power and voltage delivery process are shown in Figure 21.

Based on the simulation results of schematic 7, after Grati GT#1.1 GSPP black-start, and filling the voltage at the 500kV Grati EHVS, the generator produces 4.5 Mvar, and the voltage at the EHVS Grati is 503.39 kV.

To provide a generator load, the Grati IBT-1 is operated to provide voltage to the 150kV Grati SS. When IBT-1 Grati enters, the generator produces 4.2 Mvar, the voltage at Grati is 488.73 kV and 151.7 kV. The generator is given a minimum load through Grati transformer-1 and Gondangwetan transformer-1. At this stage, the generator produces 13.4 Mvar, the voltages are 484.99 kV and 149.72 kV.

The process of sending power and voltage to the Grati SS begins with operating the Grati – Gondangwetan conductor, followed by the Gondangwetan – Probolinggo conductor, the Probolinggo – Kraksaan conductor, and the Kraksaan – Paiton conductor. For each SS with voltage, a distribution transformer is given to meet the generator's minimum loading and maintain the network voltage and Mvar of the generator.

From the simulation results, the data obtained for all stages, the generator produces 3.9 Mvar - 13.4 Mvar, the 500 kV side voltage gets 484.99 kV - 503.39 kV data, and on the 150kV side (end side) data is 149, 39 kV – 151.79 kV.

Table 11. Stages in Scheme 7

No	Stages	Description
1	GSPP GT#1.1	Black-start
2	Busbar of 500kV Grati	500kV Grati EHVS voltage
3	Grati IBT-1	150kV Grati SS voltage
4	Grati transformer -1	Grati distribution transformer operating with a load of 5 MW
5	150kV Grati – Gondangwetan conductor	150kV Gondangwetan SS voltage
6	Gondangwetan transformer -1	Gondangwetan distribution transformer operating with a load of 25 MW
7	150kV Gondangwetan - Probolinggo conductor	150kV Probolinggo SS voltage
8	Probolinggo transformer -1	Probolinggo distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
9	150kV Probolinggo - Kraksaan conductor	150kV Kraksaan SS voltage
10	Kraksaan transformer -1	Kraksaan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
11	150kV Kraksaan - Paiton conductor	voltage up to 150kV Paiton SS to send power to the SST generator in Paiton

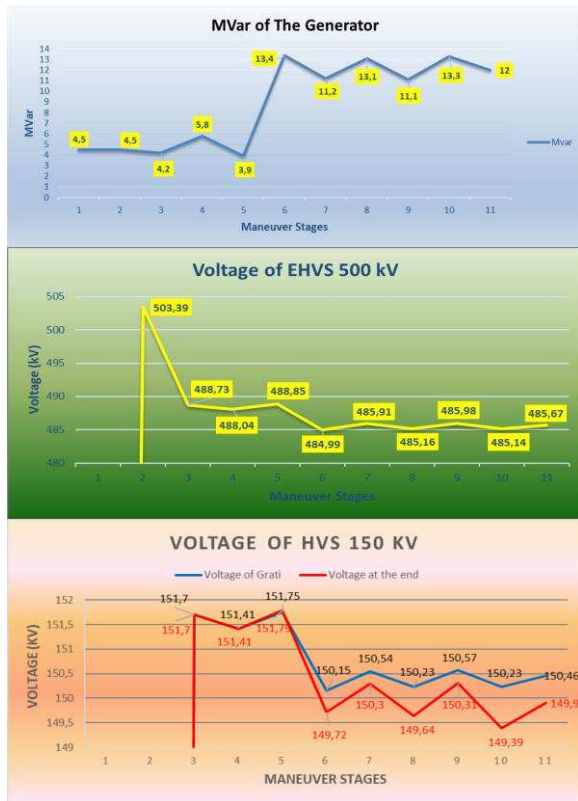


Figure 21. Mvar of Generating and Voltage on Schematic 7

The voltage delivery from Grati to Paiton has been successfully carried out, and the voltage when it reaches the Paiton SS is 149.9 kV, then it can be continued to operate the Paiton ESPP Generator SST so that the generator is immediately operated for system recovery.

Simulation of Power Delivery and Voltage Schematic 8

In this scheme, after the black-start of the Grati GT#2.1 GSPP Generator, power and voltage are sent to Paiton via 150kV transmission in stages via Grati SS –Pier SS – Gondangwetan SS –Probolinggo SS – Kraksaan SS – Paiton SS. The stages in scheme 8 are shown in Table 12.

The magnitude of the Mvar of the Grati GT#1.1 GSPP Generator and the Voltage on the Network during the process of sending power and voltage are shown in Figure 22. The simulation results of schematic 8, after Grati GT#2.1 GSPP black-start, and filling the voltage at the 150kV Grati SS, the generator produces 0 Mvar. The generator is given a minimum load through Grati transformer-1 and Gondangwetan transformer-1. At this stage, the generator produces 9 Mvar and a voltage of 148.07 kV.

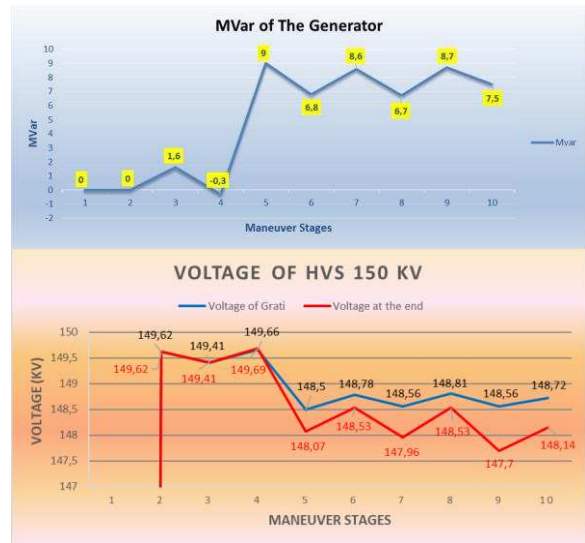


Figure 22. Mvar of Generating and Voltage on Schematic 8

The process of sending power and voltage to the Grati SS begins with operating the Grati – Gondangwetan conductor, followed by the Gondangwetan – Probolinggo conductor, the Probolinggo – Kraksaan conductor, and the Kraksaan – Paiton conductor. For each SS with voltage, 1 distribution transformer is given to meet the generator's minimum loading and maintain the grid voltage and Mvar of the generator.

From the simulation results, obtained data for all stages, the generator produces -0.3 Mvar – 9 Mvar, and a voltage of 150kV (end side) obtained data of 147.7 kV – 149.69 kV. The voltage delivery from Grati to Paiton was successfully carried out, and the voltage when it arrived at the Paiton SS was 148.14 kV, then it could be continued to operate the Paiton ESPP SST so that the generator was immediately operated for system recovery.

Comparison of Simulation Results of All Schemes

The results of the comparison of all schemes can be seen in Table 13. From the simulation results in Table 13 and analysis of all power and voltage delivery schemes from Grati SS to Paiton SS after the GSPP black-start, it can be seen that the delivery of power and voltage through the 500kV Grati – Paiton transmission line is not possible, because the Mvar of the generator exceeds the maximum absorption limit, and the voltage at the ends is far below the allowable nominal.

Table 12. Stages in Scheme 8

No	Stages	Description
1	GSPP GT#2.1	Black-start
2	Busbar of 150kV Grati	150kV Grati SS voltage
3	Grati transformer-1	Grati distribution transformer operating with a load of 5 MW
4	150kV Grati - Gondangwetan conductor	150kV Gondangwetan SS voltage
5	Gondangwetan transformer-1	Gondangwetan distribution transformer operating with a load of 25 MW
6	150kV Gondangwetan - Probolinggo conductor	150kV Probolinggo SS voltage
7	Probolinggo transformer -1	Probolinggo distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
8	150kV Probolinggo - Kraksaan conductor	150kV Kraksaan SS voltage
9	Kraksaan transformer -1	Kraksaan distribution transformer operating with a load of 5 MW (maintaining Voltage and Mvar of Grati Generating)
10	150kV Kraksaan – Paiton conductor	voltage up to 150kV Paiton SS to send power to the SST generator in Paiton

Table 13. Simulation Results of All Schemes

No	Schemes	Number of Stages	Production from Generator		Edge Voltage	
			MW	Mvar	Side of 500kV (kV)	Side of 150kV (kV)
1	1	8	30	4.5 ; 4.5 ; 4.2 ; 5.8 ; 3.8 12.4 ; -30.8	354.12	109.37
2	2	8	30	0 ; 0 ; 1.6 ; -0.3 ; 7.9 ; 7.9 ; -30.8	348.93	104.93
3	3	15	45	4.5 ; 4.5 ; 4.2 ; 5.8 ; 3.7 ; 5.1 ; 4.6 ; 12.4 ; 11.3 ; 13.2 ; 11 ; 13.2 ; 11.2 ; 13.7 ; 12.4	485.56	148.96
4	4	14	45	0 ; 0 ; 1.6 ; -0.4 ; 0.9 ; 0.5 ; 8 ; 6.9 ; 8.8 ; 6.6 ; 8.6 ; 6.7 ; 9.1 ; 7.8	-	147.18
5	5	13	40	4.5 ; 4.5 ; 4.2 ; 5.8 ; 3.7 ; 5.1 ; 4 ; 11.7 ; 9.5 ; 11.6 ; 9.6 ; 11.9 ; 10.6	486.23	149.47
6	6	12	40	0 ; 0 ; 1.6 ; -0.4 ; 0.9 ; -0.1 ; 7.3 ; 5.2 ; 7.1 ; 5.2 ; 7.4 ; 6.2	-	147.62
7	7	11	40	4.5 ; 4.5 ; 4.2 ; 5.8 ; 3.9 ; 13.4 ; 11.2 ; 13.1 ; 11.1 ; 13.3 ; 12	485.67	149.9
8	8	10	40	0 ; 0 ; 1.6 ; -0.3 ; 9 ; 6.8 ; 8.6 ; 6.7 ; 8.7 ; 7.5	-	148.14

Based on the analysis of the results, the most optimal scheme is scheme 8, namely the distribution of power and voltage through Grati GT# 2.1 GSPP (150kV) with the distribution line Grati SS - Gondangwetan SS - Probolinggo SS - Kraksaan SS - Paiton SS. This scheme has the least number of stages, namely 10 stages. The generator produces - 0.3 Mvar to 9 Mvar and a final voltage of 148.14 kV.

If the GSPP Grati that successfully black-started is the GSPP GT# 1.1 (500kV), then the optimal scheme is scheme 7, namely the distribution of power and voltage through Grati IBT – Grati SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS. This scheme has a minimum number of stages, namely 11 stages. The generator produces 3.9 Mvar to 13.4 Mvar and a final voltage of 149.9 kV.

CONCLUSION

From the simulation results using the DigSILENT software, with several previously analyzed schemes, power and voltage delivery from Grati SS to Paiton SS can be done after Grati GSPP successfully black-start. The optimal distribution of power and voltage obtained can speed up the disturbance recovery process when a blackout occurs in the Java Interconnection System and the 150kV Grati-Paiton SS. Thus, a Standard Operating Procedure (SOP) for blackout recovery for Grati-Paiton SS can be made, which previously used the Sutami HPP as a black-start source with the most optimal power and voltage delivery scheme determined from the simulation results. This SOP will later be used as a real-time operation guide (Dispatcher) for recovery when a total outage occurs at Grati-Paiton SS.

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