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# Study of power and voltage delivery after successfully black-start

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***Abstract***
*Efforts to maintain 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 that has 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 of optimal power flow simulation in distributing power and voltage, using DigSILENT software. Based on the simulation results, there are several schemes used to distribute power and voltage from the Grati-Paiton substation within the generator's Mvar, and 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 end of the Paiton substation still meets the nominal voltage according to the Grid.*

***Keywords:***
*Grati-Paiton substation, Black-start, DigSILENT*

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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 for the continuity of activities in each of these fields. Maintaining the continuity of electricity distribution to customers is very important and is a responsibility that must be 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 [1].

Disturbances that may occur 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 : [2, 3, 4]

1. September 28, 2003, in Italia and Swiss
2. August 18, 2005, in Java Bali - Indonesia
3. November 10–20, 2009 in Brasil 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 cases of blackout a power grid can be recovered with the help of another power grid system that is still operating [5][6]. However, when an electrical system blackout occurs and does not have a network that is connected to other electricity networks, it is necessary to have a generating that can be operated without the help of power and voltage from the network (black-start). Units with black-start facilities are generally small units that will not be able to restore most of the lost load but are used to supply power and voltage to larger power plants, to start the process of restoring power grid failure [2][7].

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. Gas-turbine-based plants can be profitably used in power system restoration [8]. 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 [2][7]. Another method used for black-start sources is the use of VSC-HVDC [9]. 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 [10] utilizes renewable energy such as biodiesel, solar, and wind systems [11][12], but microgrids have limitations in terms of capacity and stability.

In the 150 kV Grati Substation (SS) – Paiton Substation (SS) as part of the Java Madura Bali 500kV Interconnection System, it 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 [13]. 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. To send voltage to the Grati SS from the Sutami HPP, the voltage is sent via 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.

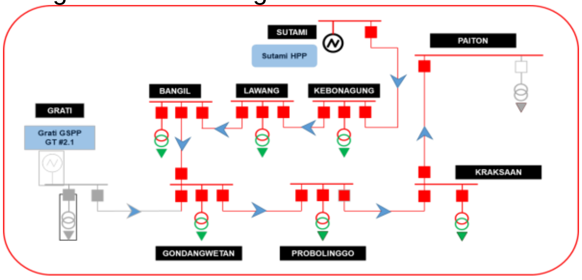



Figure 1. Black-start Grati SS – Paiton SS from Sutami HPP

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, then be able to provide power to the generator in Paiton SS. 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 that the duration of the outage is also getting longer, and the Energy Not Distributed (END) is also getting bigger.

This obstacle can be seen during the black-start test using the Dispatcher Training Simulator (DTS), where the black-start test and voltage delivery to Grati and Paiton require an average time duration of up to 3 hours until the Grati GSPP can be generated, also during the black-start test and line charging of the hydropower plant. Sutami in real-time on March 8, 2020. 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 methods of starting a black-start include using a diesel generator, gas turbine, compressed air storage, and so on. These methods have different approaches and depend on several factors, such as cost, complexity, availability of energy sources, interconnectivity with other generating networks, as well as 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. The installation of a black-start facility at the Grati GSPP will speed up the delivery of voltage and power to the generating at the Paiton SS and will speed up the fault recovery process and reduce the duration of outages which also means that END can be reduced or minimized. The planning of the power delivery scenario needs to consider several things such as the selection of the voltage delivery line, the length of the delivery line, and the calculation of the power flow.

A strategy for sending power and voltage from Grati SS to Paiton SS is needed after the Grati GSPP has 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 [14][15] 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 [10][16]. Optimal Power Flow can be done using the ETAP Power Station software [17][18]. Both of this software have limitations compared to DIgSILENT software. The usability comparison between DigSILENT and Matlab/Etab software [19] is shown in Table 1.

In this discussion, the author conducts a power flow study for 8 cases of power and voltage delivery from the Grati SS to the Paiton SS, to determine the most optimal voltage delivery path. Black-start testing in fault recovery is not possible to be carried out directly but is carried out with an approach through simulation using software [2, 7, 20]. 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 |

## DATA AND RESEARCH METHODOLOGY

### Data

The Grati - Paiton SS is part of the Java Bali Electrical Interconnection Network System [21]. The Grati - Paiton SS 150kV serves the power needs for 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.

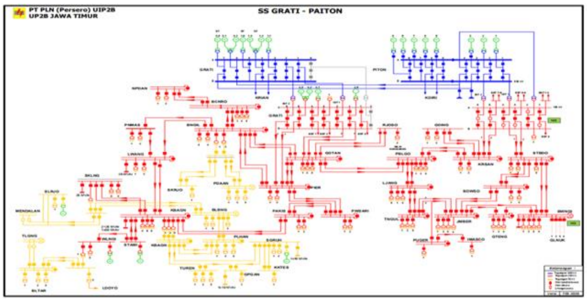


Figure 2. Grati - Paiton SS 150kV

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 source of power for the Java-Bali electricity interconnection network from the East. Table 3 shows the 500kV generation located in the Grati - Paiton SS.

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 |

When the Java-Bali Electricity Interconnection Network experienced a blackout, to build of the system, was started with the black-start process of generating that have 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, 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-start, 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 that can be used as a power delivery line from the Grati SS to Paiton SS, and the transformator data installed on each SS on the line.

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 | Gondang-wetan | Probolinggo | 150 | 33.83 | 630 |
| 7 | Probolinggo | Kraksaan | 150 | 30.24 | 1190 |
| 8 | Kraksaan | Paiton | 150 | 19.78 | 1190 |

## 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. 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.

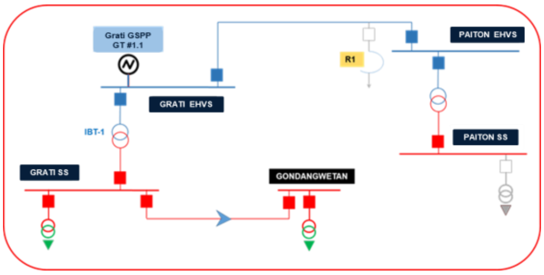



Figure 3. Power and Voltage Delivery Lines in Schematic 1

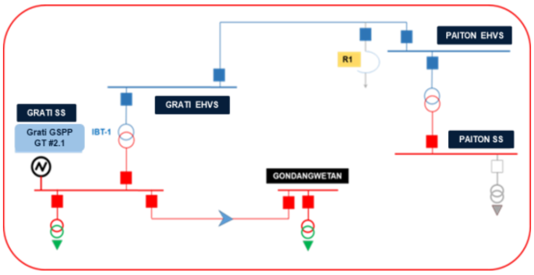



Figure 4. Power and Voltage Delivery Lines in Schematic 2

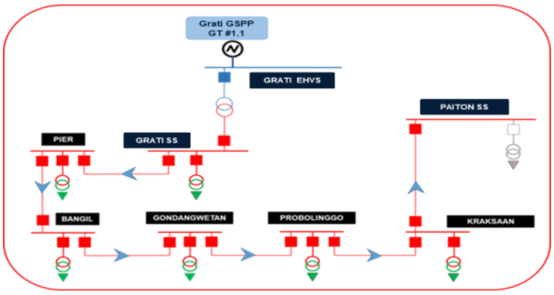



Figure 5. Power and Voltage Delivery Lines in Schematic 3

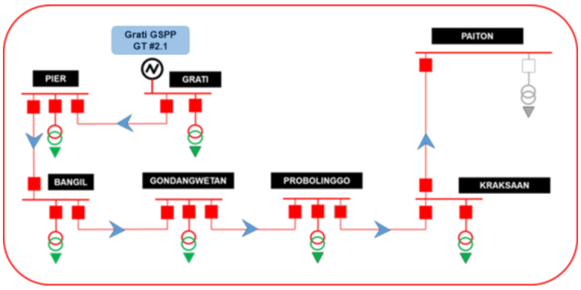



Figure 6 Power and Voltage Delivery Lines in Schematic 4

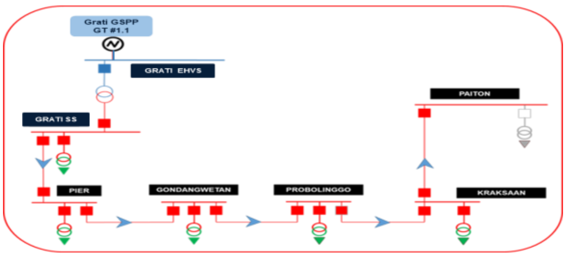



Figure 7. Power and Voltage Delivery Lines in Schematic 5

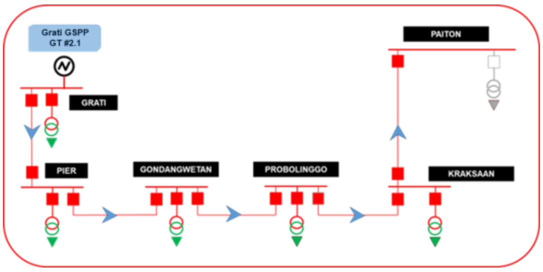



Figure 8. Power and Voltage Delivery Lines in Schematic 6.

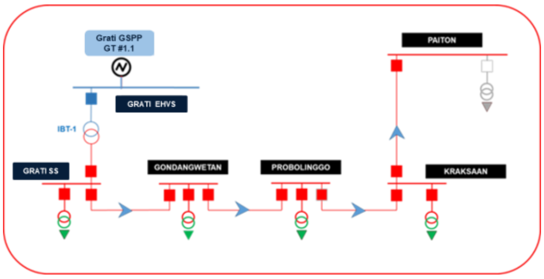



Figure 9. Power and Voltage Delivery Lines in Schematic 7.

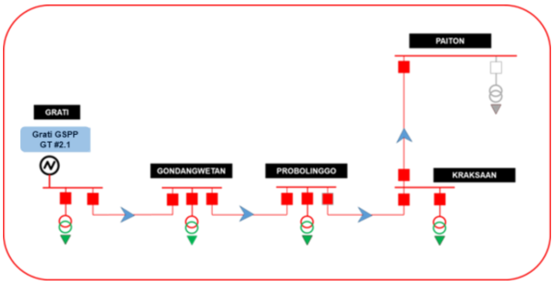



Figure 10. Power and Voltage Delivery Lines in Schematic 8

The modeling of the Power and Voltage Delivery scheme from the Grati SS to the Paiton SS after the Grati GSPP successfully black-start on the DigSILENT software was carried out to be able to plan all possible power and voltage delivery schemes and the most optimal scheme to be used as the main strategy for recovery in the event of a blackout.

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 are starting by activating the Java Bali electricity network database on the DigSILENT application.

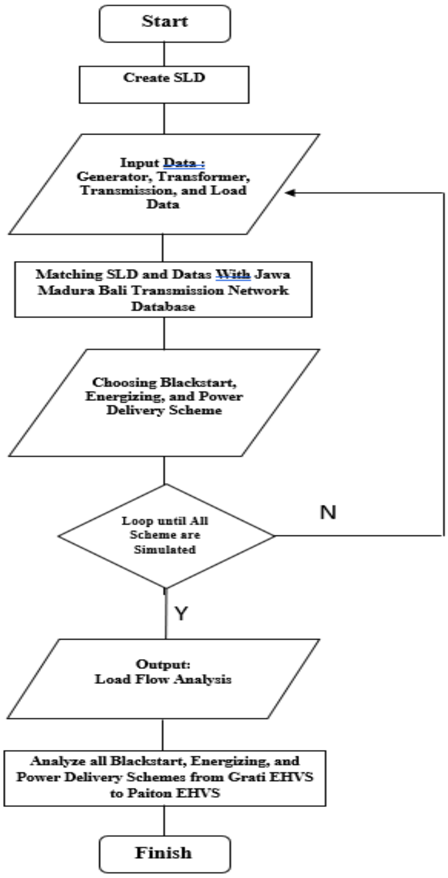



Figure 11. Flowchart of Schematic Modeling on DigSILENT

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

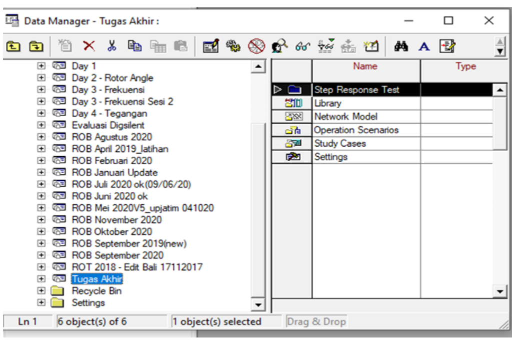



Figure 12. Database on DigSILENT

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

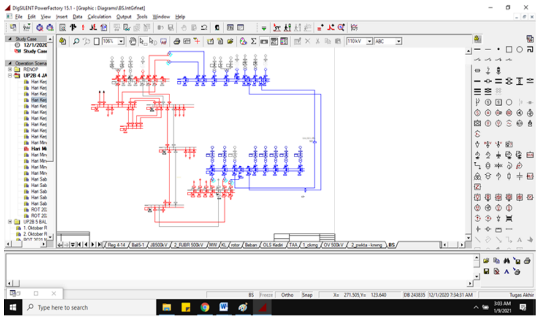


Figure 13. SLD modeling on DigSILENT

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 simulation

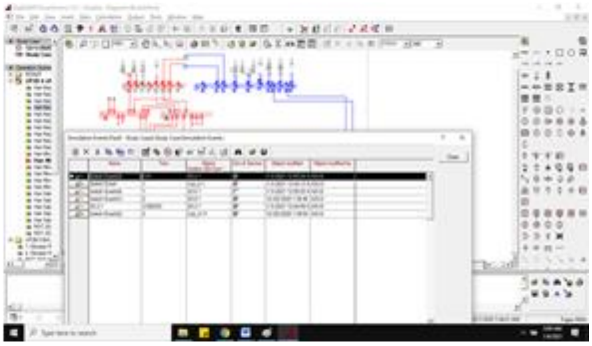


Figure 14. Schematic drawing of power and voltage delivery on DigSILENT

## RESULTS AND DISCUSSION

### A. 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 power and voltage are sent through 500kV transmission, the generator is given a load from the distribution transformer of 30MW according to the minimum load declared by the generator. The load transformer is taken from Grati SS and Gondangwetan SS.

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.

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 |
| 4 | Grati transformer-1 | Grati distribution 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 |
| 8 | Paiton IBT-1 | IBT-1 enter, voltage to 150kV Paiton SS to send power to the SST generator in Paiton |

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 15.

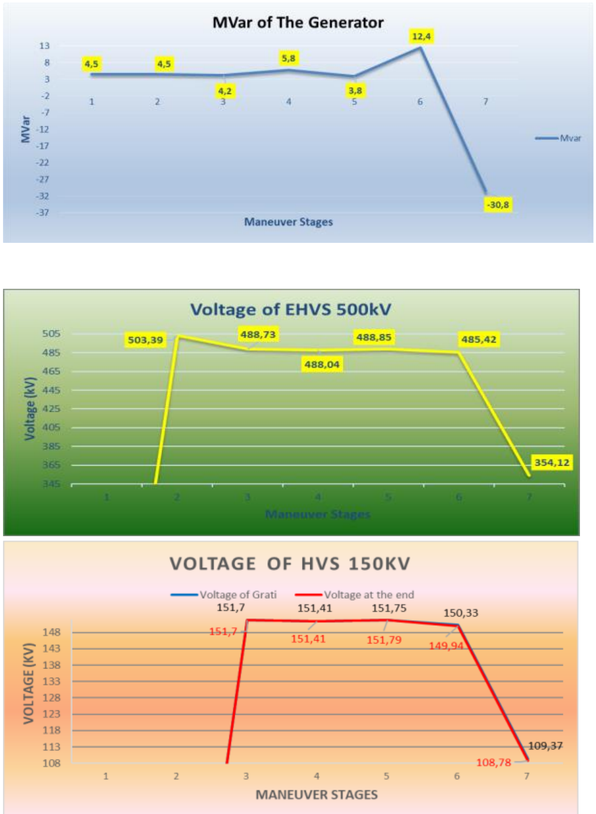



Figure 15. Mvar of Generating and Voltage on Schematic 1

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). 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.

## B. 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 GSPP Generator and the Voltage on the Network during the process of sending power and voltage are shown in Figure 16.

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 |

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. 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 voltage at Grati is 348.93 kV and 105.52 kV, below the minimum voltage limit of 500kV and 150 kV.

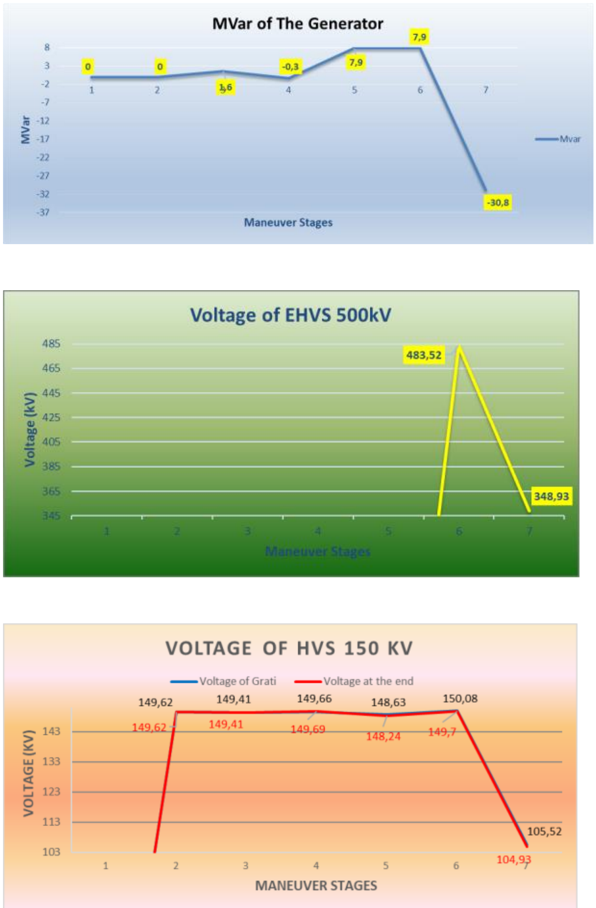



Figure 16. Mvar of Generating and Voltage on Schematic 2

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.

## C. 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 GSPP Generator, the voltage on the network during the process of sending power and voltage is shown in Figure 17.

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 |

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.

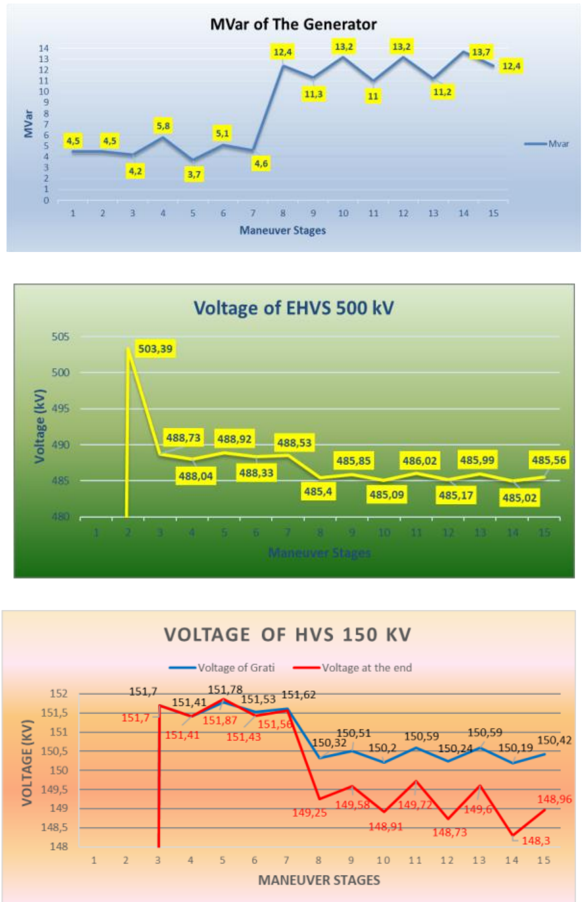



Figure 17. Mvar of Generating and Voltage on Schematic 3

The voltage delivery from Grati to Paiton was successfully carried out, and the voltage 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.

## D. Simulation of Power and Delivery on Schematic 4

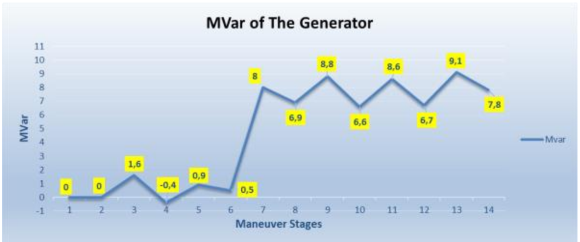
In this scheme, after the black-start Grati GT#2.1 GSPP Generator, power and voltage are sent to Paiton via 150kV transmission in stages via Grati SS – Pier SS – Bangil SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS. The stages in Scheme 4 are shown in Table 8 The magnitude of the Mvar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

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 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.
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.



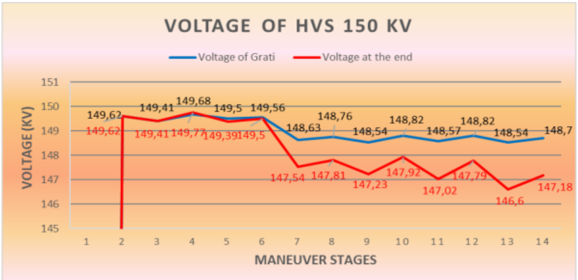




Figure 18. Mvar of Generating and Voltage on Schematic 4

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.

The voltage delivery from Grati to Paiton was successfully carried out, and the voltage 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.

## E. 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.

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 Kraksan 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 |

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.

To provide a generator load, the Grati IBT-1 is operated to provide voltage to the 150kV Grati SS. 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. 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, a distribution transformer is given to meet the minimum loading of the generator and to maintain the grid voltage and Mvar of the generator.

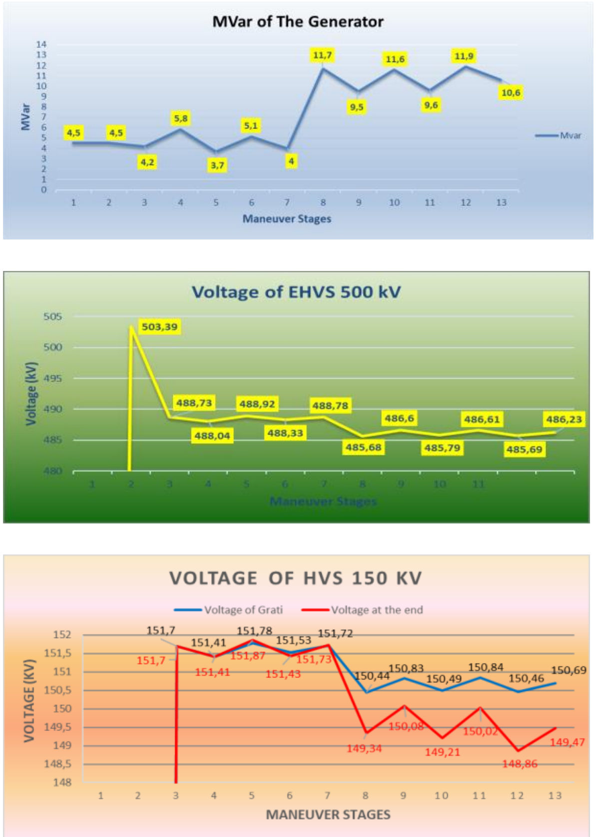



Figure 19. Mvar of Generating and Voltage on Schematic 5

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.

## F. 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.

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 |

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. 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 a voltage of 147.6 kV in Figure 20.

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 minimum loading of the generator and to maintain the grid voltage and Mvar of the generator.

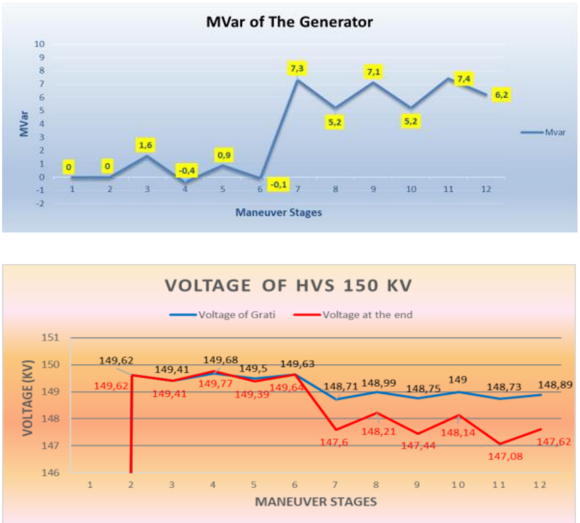



Figure 20. Mvar of Generating and Voltage on Schematic 6

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.

## G. 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.

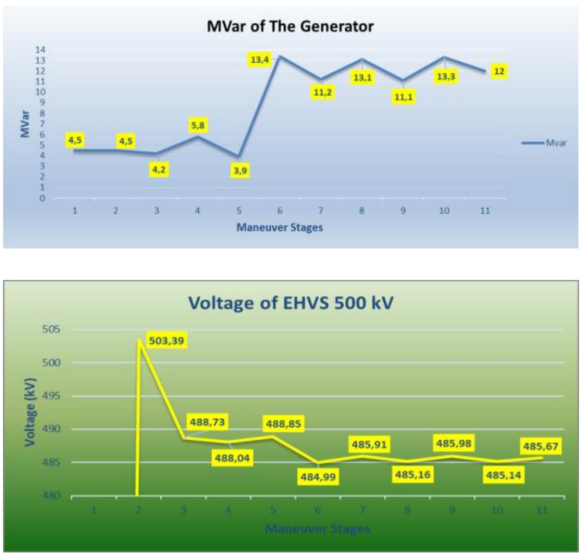
The magnitude of the Mvar of the Grati GT#1.1 GSPP generator and the connection to the network during the power and voltage delivery process are shown in Figure 21.

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.

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 |

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 minimum loading of the generator and to maintain the network voltage and Mvar of the generator.



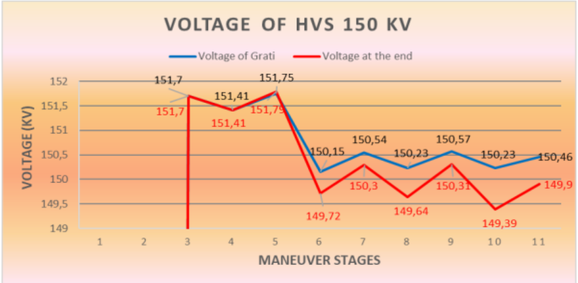



Figure 21. Mvar of Generating and Voltage on Schematic 7

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.

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.

## H. Simulation of Power Delivery and Voltage Schematic 8

In this scheme, after the black-start of 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.

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 minimum loading of the generator and to maintain the grid voltage and Mvar of the generator.

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 |

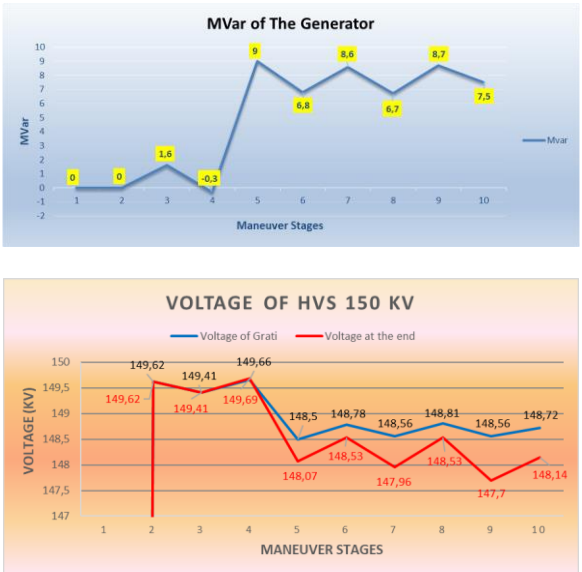



Figure 22. Mvar of Generating and Voltage on Schematic 8

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.

## I. Comparison of Simulation Results of All Schemes

The results of the comparison of all schemes can be seen in Table 13.

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 |

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.

Based on the results of studies that have been carried out that the most optimal scheme is the 8th scheme, namely the delivery of power and voltage through the Grati Block 2 GSPP (150kV) with the delivery route of Grati SS - Gondangwetan SS - Probolinggo SS - Kraksaan SS - Paiton SS because it has the least total number of stages, which is 10 stages, the generator produces - 0.3 Mvar to 9 Mvar and voltage up to the end of 148.14 kV.

Meanwhile, if the Grati GSPP that has successfully black-start is GSPP Block 1 (500kV), then the optimal scheme is the 7th scheme, namely the delivery of power and voltage through the Grati IBT – Grati SS – Gondangwetan SS – Probolinggo SS – Kraksaan SS – Paiton SS because it has the least number of total stages, which is 11 stages, the generator produces 3.9 Mvar to 13.4 Mvar and the voltage up to the end 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 in particular. 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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