Study of power flow and stability for a hybrid diesel-PV power system in Indonesia

W Soefian¹, R Azka¹, F H Jufri¹,², D R Aryani¹,², and A R Utomo¹,²*

¹Department of Electrical Engineering, Universitas Indonesia, Depok, Indonesia
²Electric Power and Energy Studies (EPES), Department of Electrical Engineering, Universitas Indonesia, Depok, Indonesia

*E-mail: arutomo@eng.ui.ac.id

Abstract. Diesel power plants are still the main choice for supplying isolated grids in Indonesia. Although this kind of power plant is easy to install, it has a high cost of energy (COE) mainly due to the cost of diesel fuel. Besides, Indonesia as a tropical country has a high intensity of solar radiation. Moreover, the investment cost of PV power plant is getting lower and it does not require high operation cost. Thus, the implementation of PV power plant is considered promising in Indonesia, and the idea of combining diesel power plants with PV in isolated grids arises to increase the efficiency of the COE. Apart from the economical aspect, the technical aspect of a hybrid diesel-PV power system implementation needs to be studied as well. In this study, the impact of the PV power plant interconnection to the existing grid is analysed in terms of the power flow and the transient stability using the DIgSILENT PowerFactory software. Furthermore, a load-sharing scheme is applied to some diesel generator units. According to the simulation result, the hybrid power system operated within the allowable voltage limits. After some transient events occurred, the hybrid power system was able to maintain its stability.

1. Introduction
Electricity consumers living in an isolated area cannot be supplied from a large grid on the main island [1]. The development of a power system in isolated areas has its own challenge, particularly due to its geographical concern which leads to difficulties in transporting the components and in providing fuel to these areas. Electric loads in these areas are mostly supplied by diesel generators which is easy to install. However, diesel generator provides another challenge since it has a high cost of energy (COE) [2].

Renewable energy sources hybridized with diesel generators or energy storage systems is one of solutions to overcome the reliability and electrification ratio issues in isolated areas, as well as to reduce fossil fuel consumption [3]. Indonesia statistically has more than 500 GW of potential solar source, so many studies propose PV power plants to be implemented in some isolated areas especially in eastern areas which have a low electrification ratio [4]. Moreover, PV power plants tend to have lower investment cost in the future. It implies that hybridizing PV power plant with diesel generators in an isolated grid can reduce the system COE. To obtain the objective of the cost efficiency, the proper optimal design and sizing method of hybrid systems are required [5],[6],[7].

Meanwhile, other studies proposed the control approach to improve the hybrid system operation. The droop control is used for load sharing scheme among the system generators consisted of voltage control, current control, and power control [8]. Another load-sharing scheme is done by using a PID algorithm to control diesel generator output for smoothing PV output fluctuation [9].
By referring to previous studies, a technical study needs to be done to observe the impact of PV power plant interconnection to the existing power system. Thus, this study analyses the power flow and the transient stability after some large disturbance occurred in the hybrid power system. Besides, a load-sharing scheme applied in diesel generator units to compensate the power deviation in the system. Governor controls of load following diesel generators are set to decrease or increase their power output as their response to system dynamics.

This paper contains four chapters. Chapter one explains the reason behind this topic being proposed by referring to similar studies that have been done before. In chapter two, the methodology of this paper is described including the system modeling and supporting data sources. Chapter three describes the simulation scenarios, the results, as well as the complete analysis. The last chapter tells about the conclusion of the simulation and analysis.

2. Methodology

2.1. Power flow and system stability

Power flow analysis solves the steady-state operation with node voltages and branch power flow in the power system [10]. This study used DlgSILENT Power Factory software with the Newton-Rapson method to simulate the power flow. This method begins with initial guesses of all unknown variables at load and generator buses [11]. To solve power flow problems, real and reactive power balance equations are generally used. Let \( P_i \) and \( Q_i \) be the active and reactive power going into bus \( i \), while \( V_i \angle \delta_i \), \( V_j \angle \delta_j \), \( \theta_{ij} \), \( Y_{ij} \), and \( n \) are voltage at bus \( i \), voltage at bus \( j \), difference in voltage angle between bus \( i \) and bus \( j \), line admittance between bus \( i \) and bus \( j \), and total bus in the system respectively.

\[
P_i = \sum_{j=1}^{n} |V_i||V_j|\cos(\theta_{ij} + \delta_j - \delta_i) \tag{1}
\]

\[
Q_i = -\sum_{j=1}^{n} |V_i||V_j|\sin(\theta_{ij} + \delta_j - \delta_i) \tag{2}
\]

Expanding the above equation in Taylor’s series,

\[
\begin{bmatrix}
\Delta P_2^{(k)} \\
\Delta P_n^{(k)} \\
\Delta Q_2^{(k)} \\
\vdots \\
\Delta Q_n^{(k)} \\
\end{bmatrix} = 
\begin{bmatrix}
\frac{\partial P_2^{(k)}}{\partial \delta_2} & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{\partial P_n^{(k)}}{\partial \delta_2} & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\
\frac{\partial Q_2^{(k)}}{\partial \delta_2} & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{\partial Q_n^{(k)}}{\partial \delta_2} & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \\
\end{bmatrix}
\begin{bmatrix}
\Delta \Theta_2^{(k)} \\
\vdots \\
\Delta \Theta_n^{(k)} \\
\Delta |V_2|^{(k)} \\
\vdots \\
\Delta |V_n|^{(k)} \\
\end{bmatrix}
\]

The terms \( \Delta P_i^{(k)} \) and \( \Delta Q_i^{(k)} \) are the difference between the scheduled and calculated values, known as the power residuals or mismatches. The partial derivatives form a Jacobian matrix. After estimating unknown variables and calculating power balance equations, mismatches, and Jacobian matrix, corrections \( \Delta \Theta_i^{(k)} \) and \( \Delta |V_i|^{(k)} \) are obtained. By adding the solved corrections to the initial estimates, the next guess of voltage magnitudes and angles is achieved. The process continues until \( \Delta P \) and \( \Delta Q \) for all buses to reach a convergent value.

Another analysis simulated is the power system stability using RMS Simulation by DlgSILENT PowerFactory software. This study is focused on frequency and voltage stability. Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset results in a significant imbalance between generation and load. Meanwhile, voltage stability is the ability of the power system to maintain a stable voltage on all buses in the system after the system is interrupted by disturbances [12].
During any disturbance, the rotor will decelerate or accelerate with respect to the synchronously rotating air gap magnetomotive force and a relative motion begins. The equation describing this relative motion is known as the swing equation which is used for analysing the transient stability [13].

\[
\frac{2H}{\omega_s} \frac{d^2 \delta}{dt^2} = P_m(p.u) - P_e(p.u)
\]  

(4)

Where \( P_m \) and \( P_e \) are the per-unit mechanical and electrical power, \( \delta \) as rotor angle, and \( H \) as per unit inertia constant. If after this oscillatory period, the rotor locks back into synchronous speed, the generator will maintain its stability.

2.2. System configuration

Figure 1(a) shows the configuration of the 20 kV hybrid PV-diesel system. Ten diesel generator units are connected to PLTD A bus, while two diesel generator units are connected to the PLTD B bus. Besides, ten 80 kW-PV arrays are connected to the PLTS C bus.

![Figure 1](image)

**Figure 1.** (a) Hybrid PV-diesel system configuration and (b) Diesel governor control block

The total load in this system is around 4.11 MW. Diesel generators DGS A typed are operated as baseload generator while DGS B, DGS C, and DGS D typed are load following generators. The load following generators are equipped with the Woodward diesel governor which the control block is shown in Figure 1(b). For load division between two or more units operating in parallel, the governors are provided with a characteristic so that the speed drops as the load is increased. The speed-droop characteristic may be obtained by adding a steady-state feedback loop around the integrator. If two or more generators with speed-droop governor characteristics are connected to a power system, there will be a unique frequency at which they will share a load change. The details of each generator type and capacities are displayed in Table 1.

| Type            | Capacity (kW) | Unit(s) | Total (kW) |
|-----------------|---------------|---------|------------|
| Base-Load Generator                  |               |         |            |
| DGS A           | 550           | 8       | 4,400      |
| Load-Follower Generator               |               |         |            |
| DGS D           | 250           | 2       | 500        |
| DGS C           | 1,000         | 1       | 1,000      |
| DGS B           | 500           | 1       | 500        |
| PV Systems      | 100           | 10      | 1,000      |

Table 1. Diesel generators and PV capacity
3. Simulation and result
3.1. Power flow result
The power flow simulation is run with DlgSILENT PowerFactory software using Newton-Rapson method. The voltage of each bus can be seen in Figure 2.

![Figure 2. The voltage of each bus](image)

Load-G has the highest voltage value with 1.021 p.u in the 20 kV network because of Load-G has two direct supply by PLTD A Bus and PLTS C Bus. Load-F Bus has the lowest voltage value with 0.971 p.u in the 20 kV network and since the load-F was the farthest load on the system, it surely has the highest voltage drop due to the line impedance. In the end, all of the bus voltages are within the allowable operating range of the studied area, i.e. 0.9 p.u–1.05 p.u.

3.2. Stability result
3.2.1. Loss of PV (1 MW). This scenario represents a 100 % PV outage. PV that initially operating with an output power of 1 MW abruptly changes to 0 MW. The trip is carried out at the t = 15s with a total simulation time of 60s.

![Figure 3. (a) System frequency and (b) bus voltages in the scenario of 100% PV outage](image)

![Figure 4. The power output of diesel generators and PV in the scenario of 100% PV outages](image)

Figure 3 is the graph of frequency (a) and voltage (b) response of the system after 100% PV loss simultaneously. At t=15s, which is the time of PV outage, the frequency graph suddenly begins to fall to the lowest point of 49.383 Hz at t = 19.9s. After that, the frequency starts to go up above for a few seconds until it reaches its stable frequency condition of 49.557 Hz at t = 54.301 s. While for voltage
response, the initial bus voltage of Bus PLTD A and PLTD B were 0.997 and 0.996 p.u. respectively then suddenly begins to fall and reach their stable bus voltage condition of 0.983 p.u. for Bus PLTD A and 0.982 p.u. for Bus PLTD B. With this disturbance, the system frequency has only decreased by 0.443 Hz and the voltage decreased by 0.014 p.u.

The initial power of DGS B, DGS D (1) and (2), DGS C, and DGS A were 0.211 MW, 0.074 MW, 0.527 MW, and 0.29 MW, respectively. At t = 15s, which is the time of PV outage, the DGS A generator oscillates for a few seconds but reaches its final output power the same as the initial value of 0.29 MW since this generator acts as a baseload generator. At the same time, DGS B, DGS C, DGS D (1) and (2) which act as a load-following generator increase their output power with a load-sharing scheme so that the four diesel generators have equal proportions of output increase. As can be seen in Figure 4, after the PV outage DGS B and DGS C are operating at 0.426 MW and 0.992 MW respectively, while DGS D (1) and (2) have the same output power, around 0.16 MW.

3.2.2. Rise of PV (1 MW). This scenario represents PV output increases 1 MW in the grid. PV that initially operating with an output power of 0 MW suddenly changes to 1 MW at t = 15s, where the total simulation time is 60s.

![Figure 5](image-url)

**Figure 5.** (a) System frequency and (b) bus voltages in the scenario of 100% PV output rise

![Figure 6](image-url)

**Figure 6.** The power output of diesel generators and PV in the scenario of 100% PV output rise

Figure 5 is the graph of frequency (a) and voltage (b) response of the system after 100% PV rise simultaneously. At t=15s, which is the time of PV output rises, the frequency suddenly begins to increase to the highest point of 50.646 Hz at t = 20.1 s. After that, the frequency starts to go down below for a few seconds until it reaches its stable frequency condition of 50.47 Hz at t = 53.75 s. While for voltage response, the initial bus voltage of PLTD A and PLTD B buses were 0.997 p.u. and 0.996 p.u. respectively, then suddenly begin to rise and reaches their stable bus voltage condition of 1.006 p.u. for PLTD A bus and 1.005 p.u. for the PLTD B bus. With 100% PV output rise, the system frequency has increased by 0.47 Hz and the voltage increased by 0.009 p.u.

Meanwhile, the initial power of DGS B, DGS D (1) and (2), DGS C, and DGS A were 0.276 MW, 0.097 MW, 0.69 MW, and 0.379 MW, respectively. At t = 15s, which is the time of PV output increase, the DGS A generator oscillates for several seconds but reaches its final output power the
same as the initial value of 0.379 MW since this generator acts as a baseload generator. At the same
time, DGS B, DGS C, DGS D (1) and (2) which act as a load-following generator reduce their power
output so that DGS B and DGS C are operating at 0.043 MW and 0.188 MW, respectively. While
DGS D (1) and (2) are operating at 0.003 MW. The load sharing scheme applied to load-following
generators makes the proportions output decrease equal for each generator.

4. Conclusion
This study analyses the power flow and the transient stability of a hybrid power system consisting of
PV and diesel generators as power sources. A load-sharing scheme is applied to load-following diesel
generators in response to system dynamics. The result of power flow simulation shows that the system
operated within safe voltage limits, with the lowest bus voltage is 0.971 p.u and the highest one is
1.025 p.u. While for power system stability, the frequency and voltage of the hybrid system are
maintained within allowable operating limits in both transient scenarios. The loss of 1 MW PV output
causes the system frequency to decrease by 0.443 Hz, and the bus voltage decreased by 0.014 p.u. On
the other hand, the rise of 1 MW PV output results in the system frequency increased by 0.47 Hz and
the bus voltage decreased by 0.009 p.u. In the other words, the hybrid Diesel-PV power system with a
load-sharing scheme applied in some diesel generator units is able to maintain its stability after some
transient events occurred. Thus, the proposed hybrid Diesel-PV power system is technically proven to
be an option for the studied isolated grid in Indonesia.

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