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Maximizing Solar Power Penetration in Off-grid Rural Areas: A Case Study on 200kWp PV-Diesel Hybrid

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Abstract — **In some rural and isolated island, electric power on the island as an off-grid system is typically supplied by diesel generators (DGs) and Solar Power Plant. The paper proposes options to maximize PV penetration in the hybrid system with minimum modification to the existing system. Modified HOMER simulation modeling is used to mimic the behavior of hybrid PV-Diesel controller. Existing DGs configuration and current load profile shall be taken into account in these options. Maximized PV penetration will decrease fossil fuel dependency, lower LCOE, reduce carbon emission and further support the government's National Energy Policy (NEP) program in renewable energy.**

Keywords* — *Microgrid, Smartgrid, HOMER, Photovoltaic, Diesel, Hybrid, Solar Power Plant, Renewable Energy

I. INTRODUCTION

A. Literature Review

Remote areas or islands in Indonesia generally lack access to main utility grid as source of electric energy. The electrification process for those areas is usually achieved by implementation of standalone power plant which commonly are diesel power plants.

While improving electrification ratio, on the other hand, The General Plan of National Energy (KEN) specified a reduction in usage of particularly oil as a form of fossil fuel. Aside from that, the increasing fuel prices, cost of fuel transportation to remote areas/islands, operation and maintenance cost in remote areas leads to insertion of solar power into existing off-grid diesel system to form a hybrid PV-Diesel generation system.

A hybrid generation system is a system with two or more forms of energy source, which are operating simultaneously and connected to a local AC distribution network [1]. In this scenario, PV shall supply additional energy to minimize genset fuel consumption. Despite its higher initial cost, PV system has low operating and maintenance cost. Therefore, PV-diesel hybrid system is subject to advantages such as:

- Lower fuel costs
- Reduced risk of fuel supply shortages.
- Lower CO2 emissions

The intermittent nature of renewable energy often limits its penetration to local grid to as low as 25% as suggested by several literature [2] [3]. However, modeling of similar system without usage of battery bank with HOMER, results in a system which does not consider the amount of available spinning reserve available on the genset. In this literature, modifications are made on the original HOMER optimization to consider the required spinning reserve on a hybrid PV-Diesel system from a case in a certain reviewed location.

B. Geographical Condition the Reviewed Solar Power Plant

The Solar Power Plant in this paper is located in a remote island with no access to high voltage/large power network. It is situated on an altitude of 10 m above sea level, using a land area of 2500 m2 with dimensions of 50m x 50m.

The Solar Power Plant is bordered by the DGs power house to the north, public road to the East, small forest the South and to the West.

C. Summary of the Reviewed Solar Power Plant

The Solar Power Plant was built in 2012 with installed capacity of 200kWp and was operated in the same year until May 2018 due to problem in the inverter component. Solar Power Plant's components consist of:

- Photovoltaic Modules - 858 units of Solarworld type SW235 Poly with a capacity of 235 Wp / unit.
- Inverter - Samil Power Solar Ocean 250 on-grid type, with a capacity of 250 kW, with an operating voltage of 450 - 820 V_{DC}.
- Photovoltaic module support - galvanized iron.

- Protection system - Inverter's internal protection function, circuit breaker and fuse.
- Cables - 4 mm2 for inter PV connection, 4 mm2 between the PV string to the combiner box, 50 mm2 for the connection between the combiner box and the inverter input terminal.
- Diesel Generators - Cummins (2 x 500kW), MTU (1 x 400kW), Komatsu (1 x 200kW) and MAN (1 x 200kW) with an operating voltage of 380-400 V_{AC}.
- Weather Station - Solar Envi Monitor (Irradiation, temperature, wind speed and direction).

II. Existing System Design and State

A. System Configuration

The configuration of the Solar Power Plant as shown in Fig. 1, is designed with a hybrid configuration between the DGs and the Solar Power Plant to serve the electric load on the main island and an adjacent small island with a peak load of 1142 kW.

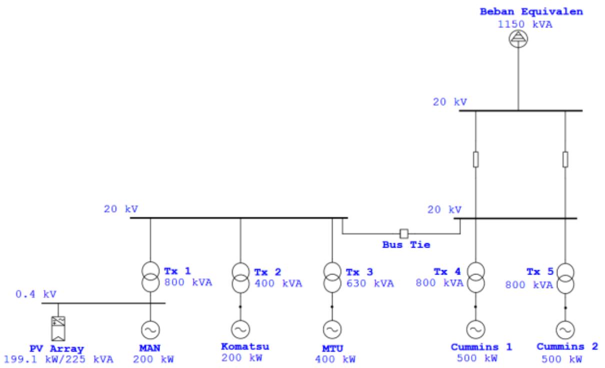


Fig. 1. Single Line Diagram of the Existing Power System

The Solar Power Plant together with DGs currently serves load which comprises ± 1700 customers in the main island and ± 300 customers on the adjacent small island in the form of both residential and public facilities (Schools, Mosques, Village Offices, Churches, Village Meeting Hall), as well as public street lighting facilities.

The total installed capacity of the Solar Power Plant is 201,630 Wp or 201.63 kWp with 858 units of 235Wp PV modules installed. The main components of solar power plant that is installed in the island are described below:

- Photovoltaic module

The specification of the installed photovoltaic module are as follows:

a. Rated Max Power (P_{MAX}) = 235 Wp

b. Short Circuit Current (I_{SC}) = 8.35 A

c. Open Circuit Voltage (V_{OC}) = 37 V_{DC}

d. Rated Current (I_{MPP}) = 7.85 A

e. Rated Voltage (V_{MPP}) = 30 V_{DC}

f. Maximum System Voltage = 1000 V_{DC}

Each PV string is composed of 22 units of modules connected in series, so from a total of 858 PV modules, there are 39 PV strings which are divided into 3 combiner boxes (13 PV strings per combiner box) as shown in Fig. 2. Output of the three combiner boxes are connected to the inverter via an underground cable at a distance of about 30 meters. The Solar Power Plant system is not equipped with a battery bank.

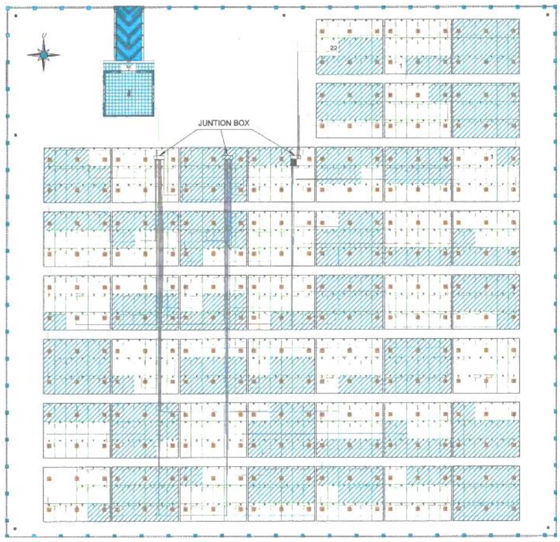


Fig. 2. Photovoltaic Modules Layout and Organization

- Inverter

The installed inverter is Samil Power inverter with a power capacity of 250 kW. The inverter output is 3 phases connected with 380V system which then feeds into a step up transformer into 20kV medium voltage grid.

Fig. 3. Samil Power Solar Ocean 250 Inverter

B. System Current State

The results of observations on the condition of the main Solar Power Plant components such as Photovoltaic modules and Inverters are provided on Table 1.

Table 1. Solar Power Plant Components

No	Component	Quantity	Remark
1	PV Modules	858	Jenis Poli-Si
2	PV Strings	39	22 modules in series

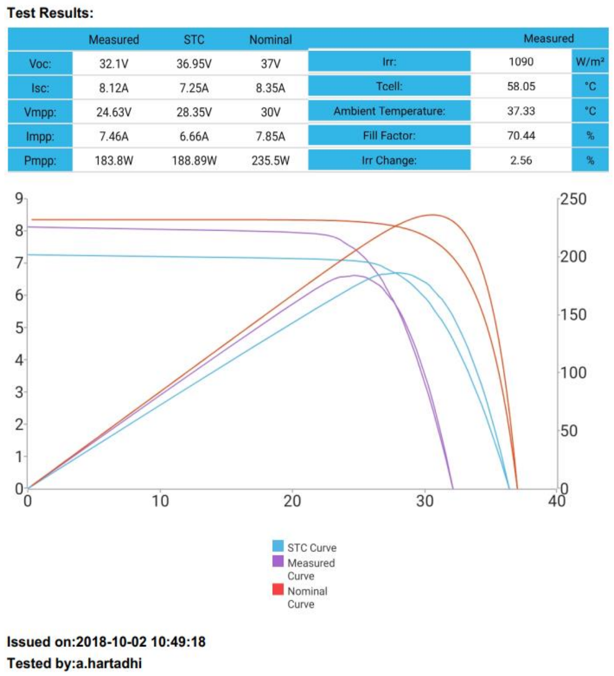
3	Module Support	48	18 modules/rig
4	Combiner Box	3	13 strings in parallel
5	Grounding	48	1 per Module Support
6	Inverter	1	AC main contactor fault

The PV array is installed facing south with tilt angle of about 10 degrees. The module's glass surface looks dirty due to dust, and a small portion of the PV array is exposed to the shadow of adjacent tree and fallen leaves.

To further evaluate the condition of the PV modules, a sample I-V curve measurement was taken on one of the modules. The measurement was taken with Seaward PV200 PV tester before and after cleaning the corresponding PV module under test. Seaward PV200 make several measurements as follows [1]:

- Voltage
- Current
- Ambient temperature
- Module temperature
- Irradiation
- Module Manufacturer & Type to determine module's alpha, beta and delta coefficients.

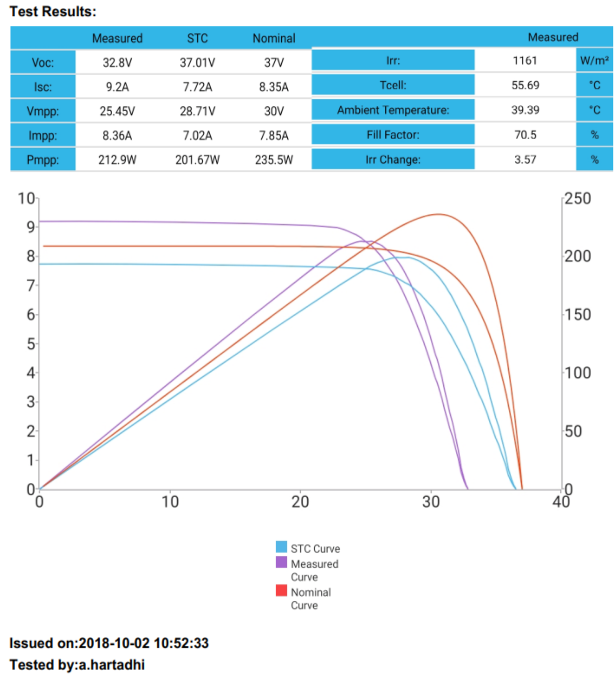
With all the above parameters, Seaward PV200 PV tester will then convert measured value into equivalent Standard Test Condition (STC) value.


Test Results:

	Measured	STC	Nominal		Measured	
Voc:	32.1V	36.95V	37V	Irr:	1090	W/m²
Isc:	8.12A	7.25A	8.35A	Tcell:	58.05	°C
Vmpp:	24.63V	28.35V	30V	Ambient Temperature:	37.33	°C
Impp:	7.46A	6.66A	7.85A	Fill Factor:	70.44	%
Pmpp:	183.8W	188.89W	235.5W	Irr Change:	2.56	%

Fig. 4. I-V Curve of PV Module Before Cleaning

Measurement results before cleaning in Fig. 4 shows the power generated by the module is 188.89 W (after conversion to STC) and the module IV curve after being cleaned in Fig. 5 shows the increase in power generated by the module by 12.78W or 6.8 %.


Test Results:

	Measured	STC	Nominal		Measured	
Voc:	32.8V	37.01V	37V	Irr:	1161	W/m²
Isc:	9.2A	7.72A	8.35A	Tcell:	55.69	°C
Vmpp:	25.45V	28.71V	30V	Ambient Temperature:	39.39	°C
Impp:	8.36A	7.02A	7.85A	Fill Factor:	70.5	%
Pmpp:	212.9W	201.67W	235.5W	Irr Change:	3.57	%

Fig. 5. I-V Curve of PV Module After Cleaning

Measurement made after cleaning shows 201.67 W PV power at STC which is still lower than 235.5 W stated by the manufacturer. According to NREL, degradation rate of poly-si PV modules installed after year 2000 is 0.64%/year as shown in Table 2. PV Degradation Rate PV derated power can then be calculated using compound formula:

$$Derated\ Power = P_{Nom}(1 - Degradation\ Rate)^n \quad (1)$$

Where: n = PV module age in years

According to the above calculation, PV module in the Solar Power Plant which are 6 years in age should have derated power of 226Wp.

Table 2. PV Degradation Rate [1]

Solar cell type	Output loss in percent per year	
	Pre	Post
Amorphous silicon (a-Si)	0.96	0.87
Cadmium telluride (CdTe)	3.33	0.4
Copper indium gallium selenide (CIGS)	1.44	0.96
Monocrystalline silicon (mono-Si)	0.47	0.36
Polycrystalline silicon (poly-Si)	0.61	0.64

III. Proposed System Modification

With the 200kWp Solar Power Plant currently not in operation, the electrical system in the island fully relies on DGs that impose high Levelized Cost of Electricity (LCOE). The load profile on the system is shown in Fig. 6. From the load curve, it can be seen that there was a load shedding scheme at 17.00 prior to load increase to peak load at 19.00.

It was caused by manual DG#3 start operation to supply sudden load increase.

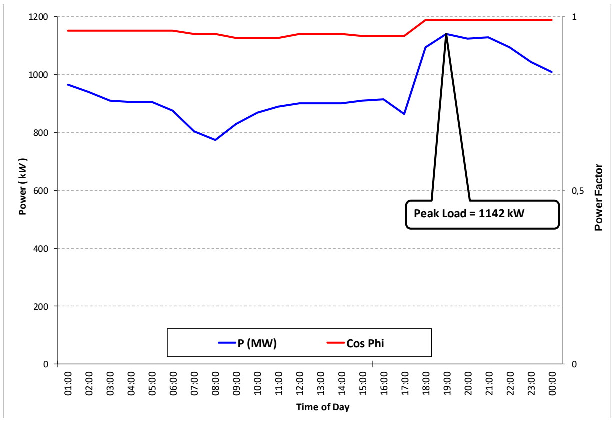


Fig. 6. Load Profile of the Island's Network on 28 September 2018

With peak load of 1142 kW as shown in Fig. 6, the power generated from the 200 kWp Solar Power Plant can be maximized with the development of smart microgrid. The development can be accomplished by installing additional module which allows direct control of inverter output/loading by taking into account the following factors:

- Load demand in the network and the historical load profile/data in the past.
- Configuration, loading and spinning reserve from the DGs.
- Configuration and power availability of the inverter.

The simple illustration of such scheme without the use of energy storage (battery) can be seen in Fig. 7.

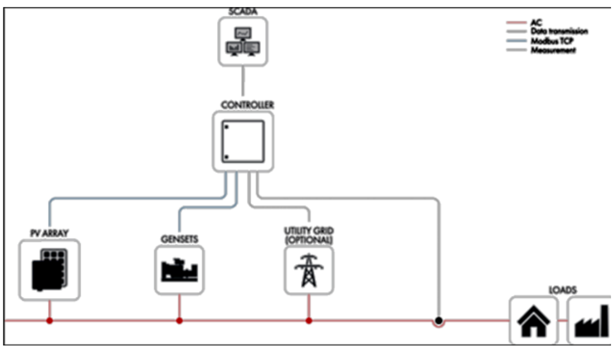


Fig. 7. PV-Diesel Hybrid Topology

With the current system, actions that need to be taken includes:

- Need immediate improvement of the Solar Power Plant system which includes:
    - Further inspection on PV modules in PV strings with abnormal voltage output.
    - Rewiring of PV strings.
    - Repair on grounding conductor of PV rig.
    - Inverter repair, preferably inverter replacement with inverter model/type that allows coordination with existing DGs so that the Solar Power Plant can supply its optimum power output to the grid.
    - Periodic cleaning of PV modules.
- Installation of generator control module to existing DGs which are MTU, MAN and Komatsu generator units so that the five existing diesel generators can coordinate and operate with isochronous load-share mode of operation.
- Installation of a smart microgrid control module that can maximize PV penetration by considering the total diesel generator capacity, inverter output and daily load profile.
- Installation of communication links for remote operation and/or data acquisition.

A. *System Development with Existing Solar Power Plant Capacity (200kWp)*

Currently, few DGs, MAN (200kW) and Komatsu (200kW) generators are only operated as a backup when maintenance is carried out on one of the 3 diesel generators (Cummins 1, Cummins 2 and MTU).

Having all DGs modernized with control modules that allow isochronous load-share mode operation, using 3 main DGs, operation of the 3 DGs will be as shown in Fig. 8

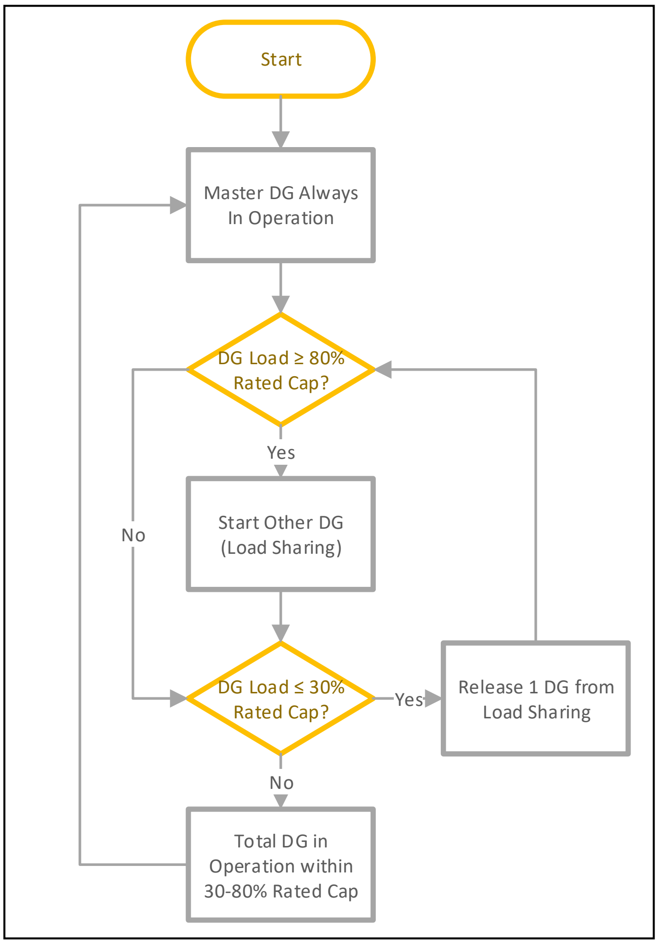


Fig. 8. Algorithm of Isochronous Load-Share Mode of DGs

With the hybrid system operating normally supplied by 3 diesel generators operating with an isochronous load-share mode and a 200 kWp Solar Power Plant, simulation was done with HOMER software with the result as shown in Table 3 and Table 4.

Table 3. Simulation Result of 200kWp Hybrid System

Waktu	Load Demand (kW)	Inverter Output (kW)	DG 1 Power (kW)	DG 2 Power (kW)	DG 3 Power (kW)	Total DG Spinning Reserve (kW)
00:00	1030	0	366	366	293	370
01:00	1031	0	348	348	279	369
02:00	903	0	330	330	264	497
03:00	902	0	325	325	260	498
04:00	999	0	325	325	260	401
05:00	963	0	325	325	260	437
06:00	967	0	313	313	250	433
07:00	816	10	282	282	226	596
08:00	738	27	267	267	214	721
09:00	816	51	268	268	214	670
10:00	882	83	274	274	219	632
11:00	892	155	259	259	207	682
12:00	992	153	267	267	213	613
13:00	896	193	253	253	202	715
14:00	913	193	253	253	202	686
15:00	912	150	273	273	219	654
16:00	961	109	288	288	230	552
17:00	986	65	316	316	253	484
18:00	1250	27	383	383	307	174
19:00	1176	0	407	407	326	224
20:00	1062	0	402	402	321	338
21:00	1159	0	402	402	321	241
22:00	1115	0	384	384	307	285
23:00	1170	0	375	375	300	230

Table 4. Simulation Summary of 200kWp Hybrid System

PV Parameters	Value	Unit
Rated capacity	200	kW
Mean output	34	kW
Mean output	807	kWh/d
Capacity factor	16,8	%
Total production	294.641	kWh/yr
Energy Production	**kWh/year**	**%**
PV array (750 kWp)	294.641	4
Cummins 1 (500 kW)	4.380.000	53
Cummins 2 (500 kW)	2.526.035	30
MTU (400 kW)	1.101.663	13
Total	8.302.340	100

From the tables above, it can be seen that with 200kWp Solar Power Plant capacity, which is ± 15% of DGs capacity, energy that comes from PV Plant is only 4% of total energy supplied to the grid. This low proportion of Solar Power Plant may be a result of PLN's regulation which limits PV power injection to the grid to 25% of feeder's peak load. [2]

It is common practice to limit uncontrolled, fluctuating renewable energy injection from PV to the grid to maintain stability of the grid. Loading profile of 200kWp hybrid system is shown in Fig. 9. From the graph, it can be seen that all 3 DGs always in operation and provide sufficient spinning reserve which is higher than inverter output.

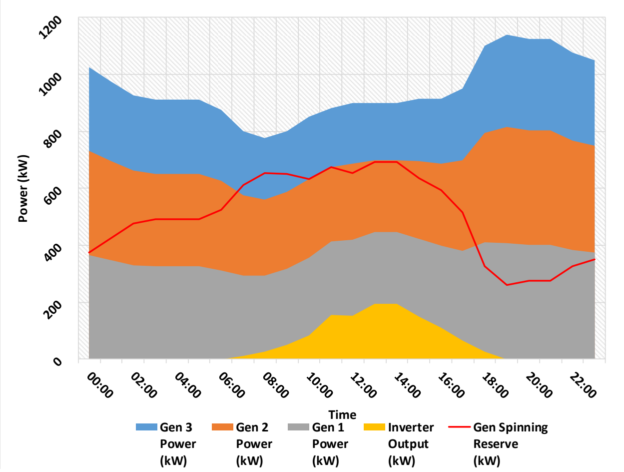


Fig. 9. Loading Profile of 200kWp Hybrid System

Thus in a situation where inverter output decreases due to shading or other disturbance in the PV system, the DGs are ready to increase their output automatically from the primary spinning reserve within seconds or milliseconds. Classification of types of spinning reserve is illustrated in Fig. 10.

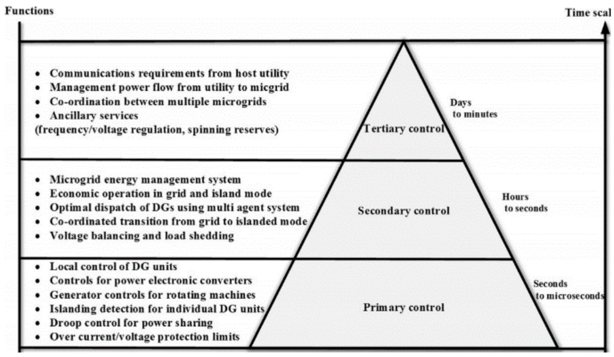


Fig. 10. Classification of Spinning Reserve Control [3]

The lowest spinning reserve is 174kW at 18.00 due to the peak load that occurs when the Solar Power Plant is operating with very low power.

B. System Development with Additional Solar Power Plant Capacity (750kWp)

With the addition of a control module for the implementation of a PV-diesel hybrid smart microgrid system, PV penetration in the network can be increased up to 60% of the peak load or total diesel generators capacity. [4]

The topology of this system which is already shown in Fig. 7. The principle of operation of this control module is to adjust/govern inverter output with respect to spinning reserve of the DGs as shown in Fig. 8.

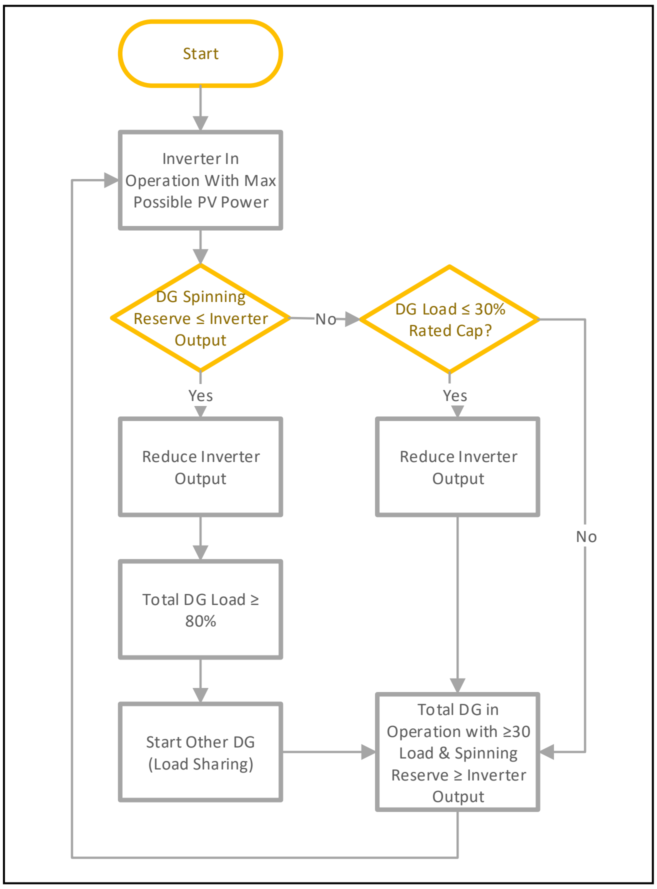


Fig. 11. Algorithm of PV-Diesel Hybrid Controller

To minimize existing system modification and enhance compatibility and reliability, connections of the hybrid controller are limited as follows:

- Communication to inverters for inverter output adjustment.
- Monitoring/reading on each DG output by means of current (CT) and potential transformer (PT)

Therefore, the hybrid controller and DG controller will work independently with their algorithm respectively.

With peak load at 1142 kW, and total installed capacity of DGs (3 main units) at 1.4 MW, this system will allow addition of Solar Power Plant capacity to 60% x 1400kW = 840kW.

Considering the load profile as in Fig. 6 which shows that load demand in time of peak sun hour is in the range of 900kW, to maintain a minimum of one diesel generator with a capacity of 400kW (MTU) continues to operate at a load of > 30% (> 120kW), then the capacity Solar Power Plant capacity should be limited to 900kW - 120 kW = 780kW ≈ 750kW.

To validate the proposed configuration, a simulation was done using HOMER with a several modifications on DGs operation timing to take account spinning reserve calculation to mimic the hybrid controller's behavior as illustrated in Fig. 11. The Simulation is carried out with configuration as follows:

- 1400kW diesel generators consisting of 3 DG units each of 500kW, 500kW and 400kW
- 750 kW Solar Power Plant consisting of 5 inverter strings with a capacity of 150kW each
- Load profile curve which is assumed to be identical to the profile of grid load on 28 September 2018 shown in Fig. 6.

Table 5. Simulation Result of 750kWp Hybrid System

Waktu	Load Demand (kW)	Inverter Output (kW)	Inverter Output (Reduced) (kW)	DG 1 Power (kW)	DG 2 Power (kW)	DG 3 Power (kW)	Total DG Spinning Reserve (kW)
00:00	1025	0	0	366	366	293	375
01:00	975	0	0	348	348	279	425
02:00	925	0	0	330	330	264	475
03:00	910	0	0	325	325	260	490
04:00	910	0	0	325	325	260	490
05:00	910	0	0	325	325	260	490
06:00	875	0	0	313	313	250	525
07:00	800	58	58	265	265	212	658
08:00	775	166	166	218	218	174	791
09:00	800	413	413	194	194	0	613
10:00	850	606	500	175	175	0	650
11:00	880	653	550	165	165	0	670
12:00	900	655	550	175	175	0	650
13:00	900	670	550	175	175	0	650
14:00	900	707	550	175	175	0	650
15:00	915	592	592	162	162	0	677
16:00	915	485	485	215	215	0	570
17:00	950	334	334	220	220	176	784
18:00	1100	103	103	356	356	285	403
19:00	1140	0	0	407	407	326	260
20:00	1125	0	0	402	402	321	275
21:00	1125	0	0	402	402	321	275
22:00	1075	0	0	384	384	307	325
23:00	1050	0	0	375	375	300	350

Altered simulation result using HOMER software is shown in Table 5 and Table 6. The original result from HOMER was aiming to maximize PV/inverter output taking into account only DG's minimum and maximum loading. Modified simulation result was made considering spinning reserve level as additional constraint.

Primary spinning reserve, which is readily available within seconds or milliseconds should always be higher than inverter output.

Table 6. Simulation Summary of 750kWp Hybrid System

PV Parameters	Value	Unit
Rated capacity	750	kW
Mean output	126	kW
Mean output	3.027	kWh/day
Capacity factor	16,8	%
Total production	1.104.906	kWh/year
Energy Production	**kWh/year**	**%**
PV array (750 kWp)	1.104.906	13
Cummins 1 (500 kW)	4.062.220	49
Cummins 2 (500 kW)	2.069.620	25
MTU (400 kW)	1.082.822	13
Total	8.319.568	100

With 750kWp Solar Power Plant, the simulation shows that the energy penetration produced by the Solar Power Plant is 1,104.906kWh / year, equivalent to 13.3% of the total energy absorbed by the network, which is around 8,300,000 kWh. With lower LCOE compared with DG, this will certainly reduce regional average LCOE as well [4].

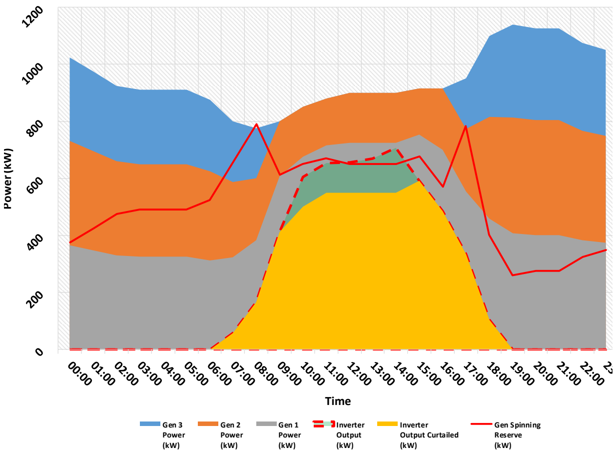


Fig. 12. Loading Profile of 750kWp Hybrid System

From Fig. 12 above, it can be seen that the inverter reduces its output to force the second DG to operate so that 2 DGs are in operation to maintain the spinning reserve level higher than inverter output. The other DG (MTU) only operate when the Solar Power Plant does not operate or operate with low power.

With spinning reserve level higher than inverter output, whenever inverter output suddenly drops due to disturbances or shading, the operating DGs will be always ready to increase their supply by means of frequency control (primary spinning reserve).

IV. Conclusion

This hybrid system can be used as a model for the implementation of the Smart Grid system with consideration:

1. The 200 kWp Solar Power Plant currently has not been fully utilized. The maximum utilization of the existing Solar Power Plant system can significantly reduce the consumption of fossil fuel by DGs.
2. Restoration/repair of the Solar Power Plant system can be done while at the same time adding enhancement to the system to support the implementation of the Smart PV-Diesel hybrid system.
3. PV power penetration can be maximized with the help of additional controller that will maintain DGs Spinning reserve higher than inverter output without directly controlling the corresponding DGs.

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