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Research Article

Technical and Economical Evaluation of Micro-Solar PV/Diesel Hybrid Generation System for Small Demand

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Abstract. This paper is intended as an investigation on a reliability of solar PV(Photovoltaic) and DG (Diesel Generator) hybrid system and the economical evaluation. In the remote area or island countries, diesel generator is a common technology for supplying power. In general, the price of diesel oil is expensive in remote areas. Therefore, introduction of the technologies which can reduce the fuel consumption for power generation is important in those area. Interconnection of solar PV with isolated diesel distribution lines is one of the options when expanding power generation facilities. However, the output of solar PV is influenced by the weather condition, it is difficult to ensure a constant output and control power amount. Using unstable input for power generation such as solar PV increases the risk of power outage due to instability of system voltage and frequency fluctuations. In this study, experiments were conducted to clarify the unstable condition using the micro-solar diesel hybrid system using solar PV (2kW), Battery Bank (24V,420Ah) and Diesel Generator (4.7kVA) and load(1500W) at Ashikaga University (AU). The experiments are conducted by two different setups, a hybrid system of solar PV and DG and the hybrid with battery bank. The results of the experiments show the frequency fluctuations becomes smaller by the hybrid system with battery bank. And the mechanical governor which attached to the DG has important function to stabilize frequency fluctuation. In the study, economic viability of the solar PV and DG hybrid system is examined by computing the Internal Rate of Return (IRR). In the calculation of the least-cost alternative system, a diesel engine powered generation system with the capacity to generate the same amount of electricity as the solar PV-DG hybrid system was used. The IRRs of the solar PV – diesel hybrid system is positive in all configuration. IRR becomes larger in the hybrid system without a battery bank and also it becomes larger with increase of the penetration ratio of solar PV. The configuration of solar PV and DG hybrid system have to be considered by the type of power demand. If the demand user requires quality power such as stabilized voltage and frequency in minimum range, battery bank have to be installed to the system. If the economical operation by saving the amount of fuel consumption is more important, battery bank does not need to be included. The system is feasible on the both aspect of technical and economical, therefore it can be introduced as reliable energy supply system for small power demand in remote areas.

Keywords: Solar PV, Diesel, Hybrid, Battery, mechanical governor, IRR

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1. Introduction

The world's population has increased 2.1 times in the past 50 years and has exceeded 7.8 billion in 2021. In addition, it is estimated that the world population will continue to increase and reach 9.7 billion by 2050. (United Nations, 2019). Developing countries account for much of this population growth, and various problems such as the increase in poverty and food shortages are occurring. In the future, it is projected that the demand for energy will increase rapidly at the same time as water, food, and environmental problems.

In 2020, primary energy demand of worldwide fell around 4% due to the COVID-19, resulting in a 5.8% drop in global energy-related carbon dioxide (CO_2) emissions. Renewable energy reached its highest recorded share which estimated 29% during periods of low electricity demand (REN21. 2021). According to the Tracking SDG7 Energy Progress Report 2021 prepared by a joint report of the custodian agencies such as the IEA (International Energy Agency) and WB (World Bank), 90.1% of the world's population was able to use electricity in 2019. On the other hand, in sub-Saharan Africa, 570 million people, which account for 46% of the regional population, do not have electricity access, and the electricity utilization rate is low as 28.1%, especially in rural areas. Electrification using distributed renewable energy has grown significantly since 2010 and has accelerated in the last few years. The number of people connecting to mini-grid using solar PV, hydro and biogas technologies more than doubled between 2010 and 2019, and 11 million people connected to the mini-grid in 2019. The connection to the solar PV mini-grid has increased about sixfold in this period and reached to 3.4 million users (International Energy Agency [IEA] 2021).

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Diesel generators are widely used to supply power in remote communities such as remote islands and rural areas in mountainous region (Journeay-Kaler & Linus. 2013). For the introduction of renewable energy to rural communities, power demand has to be considered in initial stage (Bassam, & Maegaard. 2004). At those area, extension of power transmission lines and distribution lines for small demand area is not economically feasible, therefore isolated power supply system such as diesel generator or solar PV system can be an option. Diesel power generation is also commonly used as a backup power source to cover loads in the event of a power grid outage (Ashari *et al.* 2001; Murphy *et al.* 2014).

At isolated area, power generation facility for large demand in communities, villages, towns, etc. are powered by several hundred kW to MW class diesel generator in typically. The power station consists of several power generation units (NESIS, 2011). Hybrid power supply system which consists of solar PV and diesel generator can be designed using HOMER software (Çetinbaş *et al.* 2019; Costa & Villalva. 2020; Purwadi *et al.* 2012) and MATLAB/SIMULINK (Hema *et al.* 2019). However, output power from solar PV fluctuates due to the uncertainty in solar radiation. It reduces the reliability of the power utility, especially when the penetration of PV power is large (Suryoatmojo *et al.* 2014). In a power distribution system, the voltage at the end user must be maintained within a certain predetermined range (101±6V, 202±20V in Japan) (Government of Japan, 2013). In the case of small systems, the distribution voltage is adjusted by balancing the transmission voltage from the substation with the load. However, if a reverse power flow on a distribution system upstream of a solar PV is occurred, it causes voltage to rise from the middle of the distribution line. Reverse flow can cause problems and which may result in deviation from the prescribed voltage at the terminal point of the line. If there is such risk, automatic voltage regulators such as "phase advanced reactive power control functions" and "output control functions" is required.

When there is no isolated power source in the small grid, in the event of an accident, the distribution line is adjusted to no voltage by opening the circuit breaker to the output side of the distribution substation to prevent electrical fires and shock. However, if there is an isolated power source and connected to the small grid, there is a possibility that the isolated power source continues islanding operation during an accident on the grid side. To avoid this situation, functions for power cut-off on the grid side, detect islanding operation on its own, and automatic parallel off from the grid are required (Japan International Cooperation Agency [JICA] & Okinawa Enetech, 2015). However, for small systems, since fluctuations on the voltage and the frequency tend to occur due to supply and demand fluctuations, the islanding operation prevention function is prone to unnecessary detections during normal operation. Therefore, the value for this detection function must be set after getting a good understanding of characteristics of the power system. If the islanding operation prevention function is activated by unnecessary detection, solar PV that connected to the grid is simultaneously shut down, power supply and demand balance is disturbed, and due to voltage drop and frequency fluctuation in the distribution line associated with this, the whole grid is at risk of becoming unstable.

In recent years, technology related to isolated power generation systems has been developed, allowing renewable energy sources to be integrated with conventional power supply systems to build microgrids (Banadaki *et al.* 2017; Lasseter et al. 2002). A battery-less solar PV-DG microgrid is used as an economical solution with a low capital cost to provide uninterrupted power supply to the load, while reducing the fuel consumption of a DG (Alramlawi *et al.* 2018; Koffi *et al,* 2022). It is also said that the system that uses battery as a storage system is more efficient and produces clean energy compared with the no storage system (Ammari et al. 2017). The hybrid system can reduce air pollutant emissions from diesel generator (Raj *et al.* 2021).

Since the output of renewable energies represented by solar PV and wind power is influenced by the unstable weather condition, it is difficult to ensure a constant output and control power amount as required. Using unstable power supplies such as solar PV increases the risk of power outage due to instability of system voltage and frequency fluctuations, so careful consideration is required to interconnection of solar PV to existing micro diesel power grid.

There are both impact on consumer and generator by the frequency fluctuation caused by solar PV. In consumers, frequency and rotational speed of a motor is proportional, so frequency fluctuations cause the motor itself to vibrate and produce heat, or irregularities in a product which is being made with the motor may occur. This would reduce the value of the product or result in the failure to meet the product's standards. In addition, electric clocks and automation equipment that operate based on the frequency of electricity is also affected. For electric clocks, it may cause them to be early or late, and with automation equipment, it may cause product irregularities. In the generator side, when frequency changes, rotational speed changes, so if there is a significant change of vibrations and stress on the mechanical system become a problem. In addition, if there is a significant change in frequency, it may cause the inability of generators to continue to operate resulting in generators stopping one after the other, and ultimately lead to a major blackout.

This paper aims to clarify the fluctuation caused by a micro solar PV and diesel hybrid power generation system. Solar PV system is a strong implementable option for enabling access to a cleaner, renewable source of energy in urban communities at no additional cost to users. The financial analysis of the home solar PV option shows a cost savings of 60–65% over the project life compared to the traditional use of diesel generators for backup power generation (Babajide *et al.* 2020).

Normally, at the existing diesel power station with large installed capacity in utility scale, rotational speed or power output of the diesel generators is controlled by operator. On the other hand, for micro-diesel generator, the fluctuation is absorbed by attached mechanical governor. In the study, experiments were conducted by the both condition of operation, fixed mechanical governor and free governor operations. And, to reduce frequency fluctuation, the hybrid system with battery bank is examined. In addition, economics of the diesel and solar hybrid system was evaluated in this study. The objective of this study is to confirm preferrable configuration of a micro hybrid system that consist of solar PV and diesel generator.

2. Methods of Experiments

2.1 Method

At the remote islands or rural communities where extension of power grid is not economically feasible, diesel generator is an option for the power supply. At the power station for community in those area, the rated power output of the DG is around several hundred kW to MW. Most of the large capacity DGs generate power at controlled rotational speed to maintain fixed rate of power output by manual or automatic operation. On the other hand, for micro diesel generators, mechanical governor is normally attached to adjust frequency fluctuation. The functions of the mechanical governor are to regulate the mean speed of an engine, when there are variations in the load. When the load on an engine increase, its speed decreases, therefore it becomes necessary to increases the supply of working fluid. In this study, relation between output from both of solar PV and DG is compared in several condition and also the system output frequency are studied. The experimental tests on solar PV and diesel hybrid generation systems are conducted in the campus area of AU. At the testing facility, there are grid-connected solar PV system (50kW) and isolated solar PV system (2kW for AC, 0.6kW for DC). For the experiments in the paper, isolated solar PV system with 2kW was used by the following conditions.

- 1 kW PV-diesel 4.7kVA system (without a battery)
- 1 kW PV-diesel 4.7kVA -battery system
- 2 kW PV-diesel 4.7kVA system (without a battery)
- 2 kW PV-diesel 4.7kVA -battery system
- 2 kW PV-diesel 4.7kVA -battery system (fix governor)

2.2 Climate at the testing facility

The hybrid system testing facility is located in Ashikaga City, Tochigi Prefecture in Japan. Tochigi Prefecture is located about 100km north of central Tokyo. Population of Ashikaga city is 149.5 thousand people. The geographical coordinates of the experimental facility are at Latitude 36°20'N, Longitude 139°26' E. Fig.1 shows monthly average temperature and precipitation as meteorological condition in 2021. Table 1 shows the monthly meteorological data. The highest daily averaged temperature of the year was recorded in August as 27.3 ℃ and the maximum temperature was 37.4℃. The lowest daily averaged temperature of the year was recorded in January as 3.2 ℃ and the minimum temperature was -7.4℃. The precipitation varies significantly throughout the year. According to the Meteorological Agency, precipitation is large in summer season and small in winter. Annual cumulative precipitation is 1217 mm and the monthly maximum is recorded in July as 272 mm. The monthly minimum precipitation was recorded in January as 21 mm.

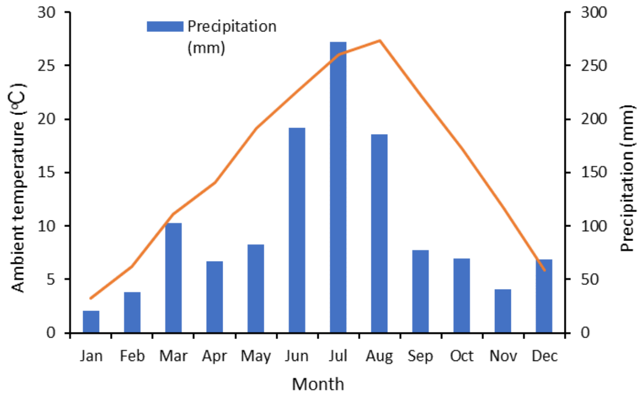

Fig. 1 Temperature and precipitation in Tochigi

Table 1
Meteorological data

Month	Precipitation (mm/Month)	Ambient temperature			Monthly wind speed (m/s)	Sunshine duration (h)
		Average (℃)	Max (℃)	Min. (℃)		
Jan	21	3.2	18.1	-7.3	1.5	188.5
Feb	38.5	6.2	23.1	-4.3	2.3	231.8
Mar	102.5	11.1	24.2	-1.2	1.6	194
Apr	66.5	14.1	27.2	1.5	1.9	224.5
May	82.5	19.1	29.8	8.5	1.6	155.5
Jun	192	22.6	31.9	14.8	1.5	136
Jul	272	26	37.1	19.4	1.3	157
Aug	185.5	27.3	37.4	18.7	1.5	157
Sep	77.5	22.2	33.2	15.3	1.3	116.5
Oct	69.5	17.2	30.7	4.1	1.3	164.3
Nov	40.5	11.7	22.4	-0.7	1.3	227.7
Dec	69	5.9	19.9	-4.8	1.7	223

Source: NEDO MONSOLA

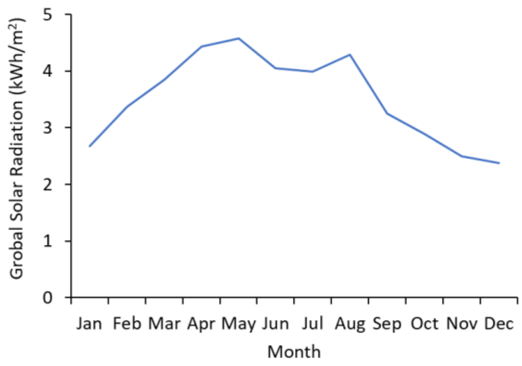

Fig.2 Global solar radiation at horizontal surface

Figure 2 shows monthly average of global solar radiation at horizontal surface from 1981 to 2009. At the Tochigi, annual average of the horizontal solar radiation was 3.52 kWh/m^2/day. The maximum monthly average solar radiation was recorded in May at 4.57 kWh/m^2/day and the minimum was recorded in December at 2.37 kWh/m^2/day. There is seasonal fluctuation on the horizontal solar radiation at the pilot site. The monthly solar radiation in May is almost double to that recorded in December.

2.2 Experiments setup

Experimental studies are conducted using micro-scale solar PV and DG hybrid system at AU as shown in the Fig. 3. The hybrid system is consisting of solar PV 2.1 kW and DG 4.7 kVA with Battery bank 24V, 420Ah. Solar PV and DG are interconnected through inverter at the system voltage of AC 200V.

Figure 4 shows the schematic diagram for the experiments. There are two 1kW PV arrays and two charge controllers in the hybrid system. Two 1kW PV arrays are connected to the battery bank. The system voltage of the DC line is 24 volts. At the hybrid system with battery bank, generated power from solar PV is charged to the battery bank through charge controller then converted to AC200V by the inverter. The output voltage of the diesel generator is AC 200V so that the system voltage at AC is decided as 200 volts. As for load, three halogen lights, each capacity is 500 Watts are used. Those lights are connected after convert to AC 100 volts through the inverter. In addition, experiments to clarify the function of a mechanical governor were conducted. The mechanical governor is used to govern the speed of diesel engines. The mechanical governor uses gears and flyweights inside the crankcase to detect changes in the load and adjusts the throttle accordingly. The crankshaft spins more slowly with the increase of engine load. This leads the flyweights to relax and the throttle to open, then the governor holds the throttle in the desired speed. It controls fuel delivery at all engine speeds and varying load conditions. In general, the at diesel power station, the function of mechanical governor is controlled to produce scheduled power output in steady condition. On the other hand, for the diesel generator for small demand, the mechanical governor is attached normally and functioning to absorb fluctuation caused by change of load. In the experiments, to find out the function of battery bank and the mechanical governor respectively. Therefore, the function of the mechanical governor is fixed in several experiments.

Table 2
Specification of Diesel Generator

Model No.		YDG600VST
Generator	Format	Self-excited rotating field type
		Three-phase alternator
	Frequency [Hz]	50
	Rated output AC (kVA)	4.7 [0.5]
	Rated voltage (V)	200
	Rated current AC (A)	13.6
	Voltage adjustment method	Transistor (AVR) with brush
	Number of phases	Single phase
	Number of poles	2
	Power factor (%)	0.8 [1.0]
	AC output terminal (V-A)	Single phase two-polex1
		Three phase terminal output
Engine	Engine name	L100V5
	Engine type	Vertical air cooled 4-cycle diesel engine
	Combustion form	Direct injection method
	Used fuel oil	Diesel light oil (JIS No.2)
	Fuel tank capacity (L)	Total amount 16.0/effective 15.5
	Lubricating oil capacity Total amount/Effective oil amount (L)	1.6/0.6
	Starting method	Electric start (Cell start)
Battery capacity (V-ah)		12-28
Length-width-height (mm)		910x527x740
Mass (kg)		180
Fuel consumption at rated load (L/Hr)		1.6

Source: Ashikaga University (2022)

Table 3
Specification of solar PV module

Item	Details
Model No.	HA-175-24
Maximum Power (P_{max})	175 Wp
Voltage at Maximum Power (V_{MPP})	32.1 V
Current at Maximum Power (I_{MPP})	5.46 A
Open circuit voltage (V_{OC})	39.4 V
Short circuit current (I_{SC})	5.79 A
Standard test conditions (STC): air mass AM 1.5, irradiance $1000W/m^2$, cell temperature 25℃	
Cell type	Monocrystalline
Number of cells	64 single crystals
Size	1,077x1,060x35mm
Weight	13.4 kg

Source: Ashikaga University (2022)

Fig.3 Overview of the testing facility

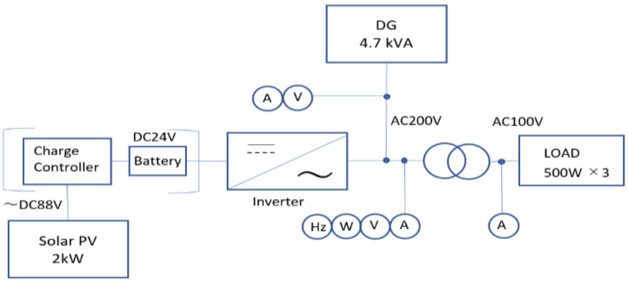

Fig. 4 Schematic diagram of PV and DG hybrid system: Diesel Generator 4.7kVA, Solar PV 2kW, DC 24V battery Bank 420Ah, Charge controller 45A, Inverter 1000W, Load 500W x 3

Operational data of the micro solar PV and diesel hybrid generator is recorded by a power logger. Table 2 shows the specification of the diesel generator. Type of the diesel engine is Vertical air cooled 4-cycle diesel engine; the engine output is 6.8kW at 3600rpm. The rated power output from the generator is 4.7 kVA, the voltage is 200 V. Table 3 shows specification of solar PV modules. The rated capacity of each solar PV module is 175 W and the cell type is monocrystalline.

3. Results

3.1 Direct: With/Without Battery

The experiments were conducted by a different setup of the hybrid system, one does not include a battery bank in the experimental setup and the other system includes a battery bank in the setup as mentioned in 2.2. Figure 5 shows the operation of the diesel 4.8 kW and a solar PV 1 kW hybrid power generation system. Battery bank is not connected in this setup. Solar PV is connected directly to the power line of the diesel generator through an inverter charger. Therefore, the fluctuations in solar radiation are transmitted directly to diesel generators. In order to absorb this fluctuation, it can be seen that the amount of power generated from the diesel increases rapidly when the solar radiation decreases rapidly. Therefore, it can be found that the frequency increases rapidly also as the solar radiation decreases sharply.

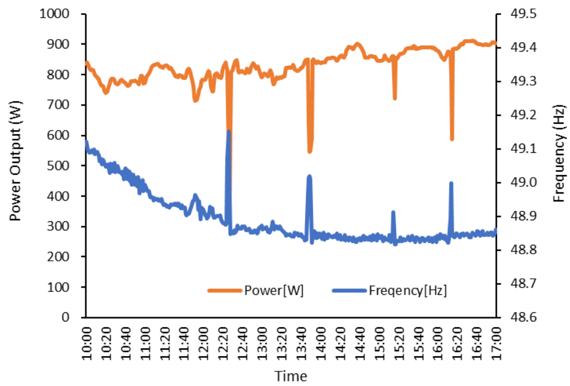

Fig. 5 Hybrid power generation system (DG and PV only)

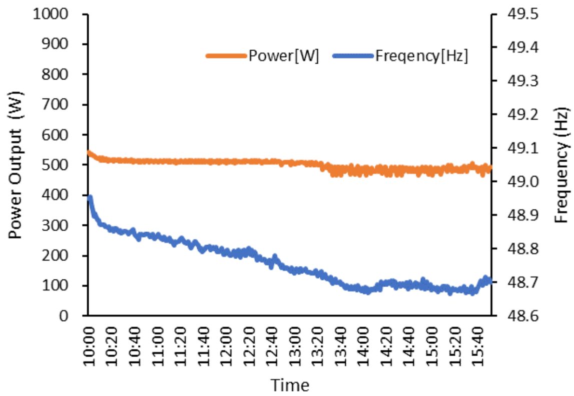

Fig.6 Hybrid power generation system (DG, PV and Battery bank)

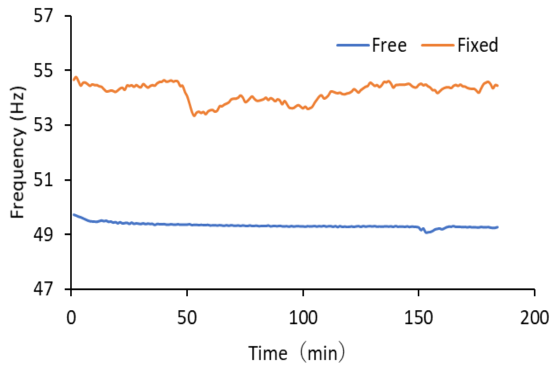

Fig. 7 Frequency (Hz) fluctuation of the operational condition of fixed mechanical governor and free mechanical governor

Figure 6 shows the operation of the diesel 4.7kW and a solar PV 1 kW and Battery bank 420Ah hybrid power generation system. Power output from the solar PV is charged to battery bank firstly then supplied to the power line of the diesel generator through charge controller and inverter. Therefore, fluctuations in solar radiation are not transmitted directly to diesel generators. Since the power generated from solar PV is first charged to the battery bank and then supplied to the diesel line through inverter, it is not affected by solar radiation fluctuations compare to the direct connection.

3.2 Direct: With / Without Governor (no battery)

In the experiment, battery bank was not connected in the system. Frequency of power output from solar PV and DG are compared by the two different conditions, one is fixed the mechanical governor which attached to the DG and the other is free operation of the governor. Figure 7 shows the frequency fluctuation of both conditions. At the free operation, the mechanical governor regulates the frequency fluctuation caused by solar PV output. On the other hand, at the fixed operation, the frequency fluctuation was not absorbed.

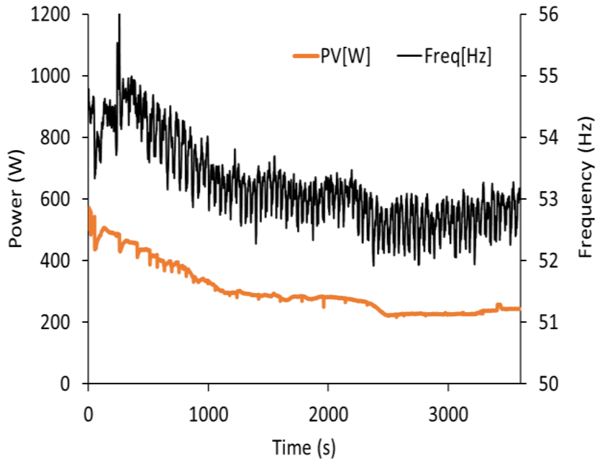

Fig. 8 Fluctuations of power (W) and frequency (Hz) at fixed mechanical governor operation

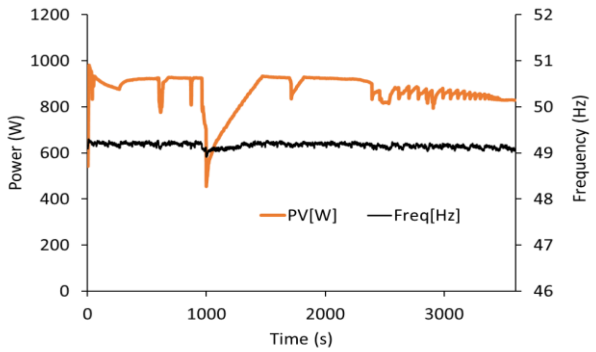

Fig. 9 Fluctuations of power (W) and frequency (Hz) at free governor operation

3.3 Battery: With / Without Governor

In this experiment, deep cycle battery was added to regulate frequency fluctuation in the hybrid system. The frequency and power were monitored by every second for 6 minutes. Figure 8 shows the fluctuation of power and frequency of fixed governor operation. The frequency fluctuation caused by the solar radiation was not absorbed well. On the other hand, Figure 9 shows that of free governor operation. At free governor operation, frequency fluctuation became smaller although fluctuation of power output from solar PV is large. The frequency fluctuation is regulated by not only the deep cycle battery but the mechanical governor.

3.4 Governor: With / Without Battery

Experiment was carried out in the to both different condition of “with battery” and “without battery”. In the both of condition, the function of mechanical governor was not fixed. Figure 10 shows the power output from solar PV and DG versus frequency of total output by the “no battery” system. Generated power from solar PV is fluctuated due to the fluctuation of solar radiation. And also, power from DG is adjusted due to the function of mechanical governor. Figure 11 shows that of “with battery”. Input power from solar PV through battery bank is stable during the operation. Because of that, input power from DG is also stable.

3.5 Fixed Gov & no Bat, vs Free Gov & Bat

Figure 12 shows the operational results of fixed governor without battery bank. The fluctuation which caused by solar radiation makes power output from the generator which consists of solar PV and DG are unstable. In addition, there is no regulation function such as battery and mechanical governor. In the figure, when power output from solar PV drops in the range of 495 W the frequency drops 3.2 Hz. It seems, the function of normal deep cycle battery for solar PV is not enough to stabilize the power output. Figure 13 shows operational results of solar PV, DG and Battery bank hybrid system. In the figure, power output from solar PV drops in the range of 479W the frequency drops 0.23 Hz only. It seems reasonable to say that fluctuation from solar PV and DG became smaller by the both function of mechanical governor and battery bank. The range of fluctuation is around 7% of that of fixed governor with battery.

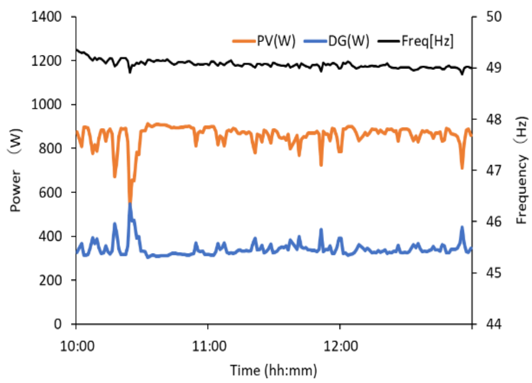

Fig. 10 Output (W) from the hybrid system (DG and PV only) and frequency (Hz) of the output from DG and PV

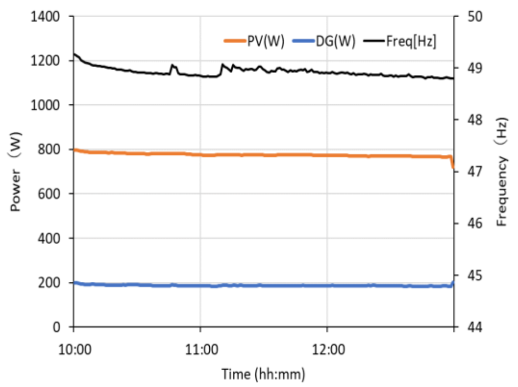

Fig. 11 Output (W) from the hybrid system (DG, PV and Battery bank) and Frequency (Hz) of the output from DG and PV

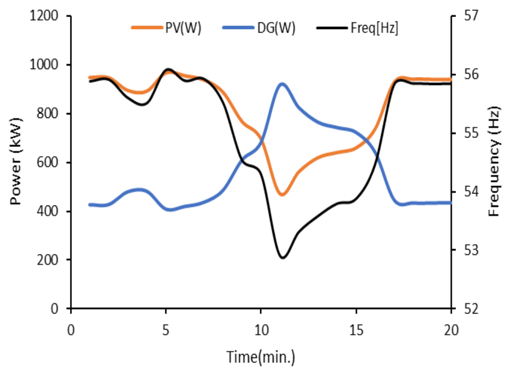

Fig. 12 Output (W) from the hybrid system (DG and PV only) at the operational condition of fixed governor

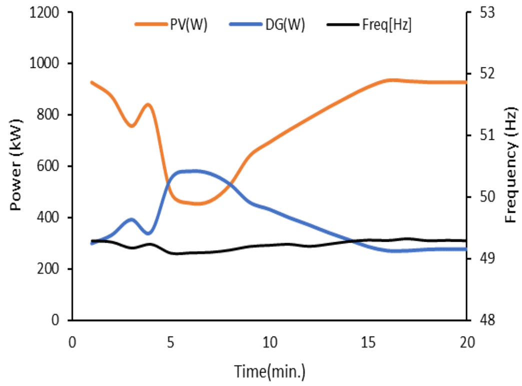

Fig. 13 Output (W) from the hybrid system (DG, PV, Battery bank) at the operational condition of free governor

3.6 Frequency

Electricity is supplied at 50Hz in the eastern part of Japan. And the target range of the standard deviation of frequency is 50±0.3Hz in Hokkaido and 50±0.2Hz in eastern Japan. In an island country, Kingdom of Tonga, the target of standard deviation is wider than that of Japan as 50±1.5%. In small load and high penetration of renewable energies, the frequency fluctuation becomes larger. Table 3 shows the range of frequency fluctuation of the micro solar PV / DG hybrid system. The standard deviation of the frequency reduced by installing the battery in the system. Comparing the frequency fluctuation of power distribution line by utility company in Japan, the standard deviation is smaller. Therefore, it can say that frequency caused by solar radiation is small. However, it can be said for micro-grid system, frequency of the load causes the frequency fluctuation (Jasemi *et al.* 2016), therefore demand side management is more important.

3.7 Fuel Consumption Rate

Table 4 shows the results of fuel consumption rate in each configuration of setup. The diesel generator consumes 0.7 litters of diesel oil per one kWh production. As shown in the table, the fuel consumption rate is improved by the hybrid system with solar PV. Fuel consumption rate was 0.51 litters per kWh in the combination with solar PV 2kW without a battery bank which is improved 28% compared to DG alone. Penetration ratio of the soler PV was around 54% in that case. On the other hand, the fuel consumption rate of the solar PV 2kW with a battery bank was 0.62 litters per kWh which improved 11% compared to DG alone.

Table 3
Range of frequency fluctuation

Frequency (Hz)	1 kW No Battery	1 kW With Battery	2 kW No Battery	2 kW With Battery
Average Frequency (Hz)	48.9	48.8	49.0	48.6
Max. Frequency (Hz)	49.3	49.0	49.3	48.8
Min. Frequency (Hz)	48.7	48.7	48.7	48.5
Standard deviation of the Frequency (Hz)	0.14	0.07	0.12	0.09

Table 4
Comparison of fuel consumption rate

System	Fuel Consumption Rate (L/kWh)	Ratio (DG /Hybrid) (%)	PV penetration (%)
DG(4.7kW)	0.70		
DG(4.7kW)+PV(1kW)	0.61	13%	26%
DG(4.7kW)+PV(1kW)+Battery	0.61	13%	35%
DG(4.7kW)+PV(2kW)	0.51	28%	54%
DG(4.7kW)+PV(2kW)+Battery	0.62	11%	44%

3.8 Economic Evaluation

The unit cost of electricity for solar PV system was higher comparing to utility electricity in 2012 (Oko *et al.* 2012). However, currently cost of PV module is decreasing. The Internal Rate of Return (IRR) is a measure of the percentage yield on investment. The IRR is compared against the investor's minimum acceptable rate of return (MARR), to ascertain the economic attractiveness of the investment. If the IRR exceeds the MARR, the investment is economic. If it is less than the MARR, the investment is uneconomic (Ruegg & Marshall. 1990). The IRR is a metric used in financial analysis to estimate the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis. IRR calculations rely on the same formula as NPV does. IRR is the annual return that makes the NPV equal to zero.

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \quad (1)$$

Where CFt is net after-tax cash inflow-outflows during a single period, r: internal rate of return that could be earned in alternative investments, t: time period cash flow is received, n: number of individual cash flows.

$$C_0 + \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \frac{C_3}{(1+r)^3} + \cdot \cdot + \frac{C_n}{(1+r)^n} \quad (2)$$

Where C_0: Initial Investment, C_n: Cash Flow, n: each period

The economic viability of the Diesel and solar PV hybrid system is examined by computing the IRR, which is calculated based on the following assumptions. The IRR method, by definition, represents the average annual rate of return with assumption that excess cash income from project will be reinvested at a rate that is exactly the same as IRR (Miletić & Latinac. 2020). Economic evaluation is examined based on the assumptions as shown in Table 5. The life of the proposed project is assumed to be 20 years and for taking into account the economic life of the solar PV, the main facility of the hybrid system. For the others, life of the micro diesel generator assumed as 7 years. In addition, the life of charge controller, inverter and battery bank are assumed as 6 years. All the costs and benefits are estimated at the price level of May 2022. Price escalation is not included in the evaluation in order to derive the IRR net of price escalation impact. Economic costs are derived by taking the domestic taxes and subsidies from the financial costs. Residual value is assumed to be zero as all the equipment is to be used up to their economic life.

Table 5
Economic Life of Major Equipment

Item	Years
Diesel Generator	7
Solar PV	20
Charge Controller	6
Inverter	6
Battery	6
Control House	20

Annual operation and maintenance costs of the project facilities are calculated based on the initial installation cost and the estimated ratio as shown in below.

Diesel Generator:	5.0%
Solar PV hybrid system:	3.0%
Distribution line:	2.5%

Economic benefits are derived by taking the domestic taxes and subsidies from the financial costs. The costs of the least-cost alternative system, i.e., a diesel engine powered generation system with the capacity to generate the same amount of electricity as the Solar PV-DG hybrid system, is considered to be the economic benefit. Investment cost of the diesel and solar PV hybrid system is estimated as shown in the Table 6.

Economic cost of diesel oil is adopted as1.2 US$ per litter. Table 7 shows energy generation and diesel cost at the solar PV penetration ratio of 10% and 20% respectively. Annual energy output from diesel generator is estimated based on 12hour operation throughout year with capacity factor of 0.9. Consumption of diesel oil is decreasing with the increase of penetration ratio of solar PV.

Table 6
Investment Cost

Item	Unit	Cost
DG	5 kVA	4,000
PV System	2kW	1,500
Charge Controller (MPPT)	50A	200
Inverter	2000 W	400
Battery	105Ah	2,400
Control House	1 house	1,000
Installation Materials	All	1,000
Installation Work	All	1,500
Total Investment Cost	-	12,000

Table 7
Energy Generation and Diesel Oil Cost

	Diesel (5kVA)	DG+PV (Penetration 10%)	DG+PV (Penetration 20%)
Energy Generation (kWh/year)	18,527	18,527	18,527
Fuel Consumption (litters/year)	12,969	11,672	10,375
Diesel Oil Cost (US$/year)	15,563	14,007	12,450

Table 8
Internal Rate of Return

	with Battery		without Battery	
	Penetration 10%	Penetration 20%	Penetration 10%	Penetration 20%
IRR (%)	20.9	74.6	54.3	242.5

Table 9
GHG emissions from diesel and PV-diesel systems (kg/year)

Pollutant	Diesel	1 kW PV/diesel	2 kW PV/diesel
Carbon Dioxide (CO_2)	3,905	3,571	3,344
Carbon Monoxide (CO)	24.4	22.8	21.3
Unburned Hydrocarbons (UHC)	1.1	1.0	0.9
Particulate Matter (PM)	0.1	0.1	0.1
Sulfur Dioxide (SO_2)	9.6	8.9	8.6
Nitrogen Oxides (NOX)	22.9	21.4	20.0

The IRRs of the three projects on the basis of the above assumptions are computed as shown in Table 8. The IRRs of the solar PV hybrid system is positive in all configuration. IRR is higher in the hybrid system which not include battery bank. In addition, IRR becomes higher with increase of the penetration ratio.

Table 8 indicates that the proposed micro-DG and solar PV hybrid system is economically viable. IRR increases by adding solar PV to DG's micro-grid, especially the system without battery bank. However, in the case of without battery bank, frequency fluctuation of the supplied power increases with increase of the penetration of solar PV. The results of economic analysis indicate, with battery bank system at the penetration ratio 20%, IRR is high as 74.6%.

3.9 Environmental Consideration

The fossil fuel-based electricity generation approaches are one of the major sources of anthropogenetic carbon dioxide emissions to the airspace (Azoumah *et al.* 2011) Consumption of diesel has a negative impact on the environment and is harmful to human health, since different kinds of gaseous pollutants are emitted during the process. (These emissions include nitrogen oxide (NOx), sulfur dioxide (SO_2), particulate matter (PM), unburned hydrocarbon (UHC), carbon monoxide (CO), and carbon dioxide (CO_2) (Aziz et al. 2019). HOMER is a software to simulate optimum configuration of hybrid system which performs three operations, namely: simulation, optimization and sensitivity analysis (Rahimi *et al*, 2019).

Using a function of HOMER (hybrid optimization of multiple energy resources) software, amount of emission of pollutants which produced from a diesel generator and the diesel/solar PV hybrid system were compared. The environmental impact of electricity generation is greatly reduced by the use of the hybrid solar PV/ Diesel/Battery system in Côte d'Ivoire (Koffi *et al*. 2022).

The hybrid system consists of a diesel generator (4.7kVA), Solar PV 2 kW, an inverter 1kW and batteries 12V. Table 9 shows the result of emissions of pollutant that produced by a diesel generator and the solar PV and diesel hybrid system. It is obvious that the amount of pollutant emission decrease with increase of installed capacity of the solar PV.

4. Discussion

For isolated power generation system, quality and quantity of electricity have to be balanced to meet requirement of demand user. Fluctuation of solar radiation cause the fluctuation of energy output from solar PV system as shown in Fig.9. In consumers, frequency fluctuations affect the rotational speed of motors, electric clocks and automation equipment. In the generator side, if there is a significant change of vibrations and stress on the mechanical system become a problem and ultimately lead to a major blackout. Micro solar PV and DG hybrid systems also need to consider the affordable range of frequency variations. Most of the small DG has attached the mechanical governor to generate stable energy output in unstable load condition. The experiments show the diesel generator can absorb the frequency fluctuation by the function of the mechanical governor as shown in figure 9 and 10. And, by connecting battery bank in the generation system, it could absorb the fluctuation more. It can be absorbed the frequency fluctuation more by adding ultra-capacitor (Diarra *et al*. 2019) or quick response battery such as lithium-ion batteries. However, the cost of lithium-ion battery needs a price reduction that most likely will be due to the mass production (Diouf & Pode. 2015). Isolated power supply system using renewable energy and battery bank has to be replace the battery bank every few years. Battery is a consumable part. This replacement cost worse the IRR of the project due to the high market price of the battery bank. On the other hand, micro solar PV and diesel hybrid system, frequency fluctuation is not too large if the mechanical governor function well. Therefore, if the end user can afford the frequency fluctuation, the hybrid system without battery bank becomes more economically feasible. If the quality of electricity is more important, frequency need to be stabilized using battery bank. At the diesel power plant that supplying power to certain area by power utility company, several number of large-scale diesel generator are being operated in many cases. An also, manual operation of the diesel generators which intelligent operating unit is not attached are still conducted. When solar PV is installed such manually operated diesel power plant, adequate method for the operations have to be established otherwise reduction of fuel consumption cannot be expected. Therefore, Energy Management System (EMS) which balance the energy production from solar PV and DG have to be installed. The intelligent control unit of the large diesel generator has similar function of the mechanical governor of micro diesel generator. So that the intelligent control unit have to be attached to the manually operated diesel generator before planning installation of EMS to reduce capacity of the battery bank. As for environmental concern, Energy payback time and GHG payback time are discussed here. Energy payback time is defined as the period required for a solar PV system to generate the same amount of energy that was used to produce the system itself (Asdrubali & Desider. 2018). According to the National Institute of Advanced Industrial Science and Technology (AIST) of Japan, EPT of solar PV is between 0.96 to 2.6 years. And energy payback time of fossil fuel thermal power station is 1.4 to 5 years in the condition of exclude fuel cost. The carbon payback time is the period between initial harvest and the point in time were the overall carbon balance equals the carbon storage before initial harvest, taken into account carbon debt and unconsumed fossil fuels (Jonker *et al*. 2014). CO_2 emission factor of the diesel is 70.4 (tonnes/1010J) which is larger than that of natural gas 50.3 (tonnes/1010J) (The LEVON Group. 2015). The amount of diesel is equal to 2552(g CO_2/kWh). On the other hand, total life cycle GHG emissions from renewables are much lower and generally less variable than those from fossil fuels. GHG emissions factors of solar PV at one-time upstream (e.g., materials acquisition and plant construction) is less than 28 (g CO_2e/kWh) and one-time downstream (e.g., plant decommissioning and disposal/recycling) is less than 5 (g CO_2e/kWh). The total life cycle emission factors for electricity are 52 (g CO_2e/kWh) and which is much smaller than that of natural gas 486 (g CO_2e/kWh) (National Renewable Energy Laboratory [NREL]. 2021). Therefore, the amount of GHG factor of the solar PV will be much smaller than that of diesel generator. Those factors mentioned here can be reduced by increasing penetration ratio of solar PV in the Diesel / Solar PV hybrid power generation system.

5. Conclusion

Renewable energy sources such as solar PV are recognized as having limited economic viability, supply stability, and geographical limitations. These results of experiments lead us to the conclusion that a hybrid system of micro-DG with solar PV and battery banks can reduce frequency fluctuations and it could supply stable frequency of energy. The function of mechanical governors which attached micro-DG normally with battery bank is also useful to stabilize frequency fluctuation in the micro hybrid system. On the other hand, in terms of improve the fuel consumption rate, the hybrid system (PV 2kW + DG 4.7 kVA) without battery bank could generate more energy than that of with battery bank because the amount energy output from solar PV is not controlled by charge controller. The result of economical evaluation shows that IRR of the hybrid system without battery bank is higher than that of the hybrid system with battery bank because periodical battery replacement cost decreased economic efficiency. Based on the results of the research, we believe that the hybrid power generation system of micro-DG and solar PV is a useful technology for supplying power to small power demand. The configuration of the hybrid system can be designed based on the both aspect of required quality of electricity and economical aspect. For further study, in the technical aspect, additional components such as quick-response batteries or ultra-capacitors that absorb frequency fluctuations have to be examined. And also, hybrid system with other renewable sources can be considered, especially wind turbine which can reduce levelized cost of electricity (Hassane *et al*. 2022). Wind turbine may cause more frequency fluctuation from input energy. In the economic aspect, improvement of the function of mechanical governor is important. And, to improve IRR, it is important to reduce the price of batteries and make them longer in life.

Solar PV and diesel hybrid system is suitable for isolated area where diesel generator is being operated for power supply. It is possible to reduce fuel consumption and emission of GHG gases by adding the solar PV to existing diesel generator. For large power station, EMS must be installed at the solar PV and diesel hybrid system to reduce fuel consumption and emission of GHG effectively. It is useful to reduce the battery capacity also. For micro hybrid system, include battery storage in the system to stabilize frequency fluctuation from the system. Solar and diesel hybrid system is recommended to install where higher solar irradiation is available and remote area where fuel cost is high. In addition, if the cost of battery storage becomes lower in future, it can be replaced only solar PV system to reduce operating cost and GHG emission.

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