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Evaluation of the Power Limitation Control System of Solar Power Plant on Production Overshoot on the Stability of the Bawean Island Electricity System as a Support for the Operation of the Bawean Island PLTMG

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ABSTRACT

The Integration of Solar Power Plants (PLTS) in isolated electricity systems provides benefits in increasing the use of renewable energy and reducing fuel consumption in conventional plants. The Bawean Island electricity system is an isolated system that utilizes solar power plants to support the operation of the Gas Engine Power Plant (PLTMG). However, in its operation, several disturbances were found caused by the phenomenon of overshoot solar power production which had an impact on the stability of the electrical system. This study aims to evaluate the performance of the power control system for solar PV power limits against the occurrence of production overshoot and its impact on the stability of the electricity system on Bawean Island. The research method was carried out through analysis of plant operation data, evaluation of solar power trends, and Fault Tree analysis to identify the main causes of disturbances. The results of the analysis show that the overshoot of solar power power occurs due to inaccuracies in the control system of the Energy Management System (EMS), especially in the PID control parameters and system protection settings. This condition caused a power surge that affected the PLTMG auxiliary system, resulting in a trip of the power plant unit and disruption of the electrical system to blackout. Therefore, it is necessary to optimize the control and protection system of solar power plants so that solar power plant operations can run more stably to support PLTMG operations on Bawean Island.

1. Introduction

The increasing need for electrical energy and the demand for reducing carbon emissions encourage the use of renewable energy sources in the electricity system in various countries. One of the rapidly growing renewable energy technologies is the Integration of Solar Power Plant (PLTS) due to the availability of abundant solar energy sources and the ease of integration with existing power generation systems [1]. The integration of solar power in the electric power system can increase the

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use of clean energy while reducing fuel consumption in fossil-based plants so that it can increase the operational efficiency of the overall electric power system [2].

In isolated electrical systems such as the Bawean Island electricity system, the integration of solar power plants has an important role in supporting the operation of the main power plant. The electricity system on Bawean Island is currently dominated by Gas Engine Power Plants (PLTMG) which function as the main source of generation, while solar PV acts as a supporting plant that helps supply some of the system's power needs. Integration of good control so as not to cause disturbances to the stability of the electric power system [3].

The characteristics of solar power output are greatly influenced by fluctuating solar radiation conditions. Rapid changes in solar radiation can cause significant changes in output power in a short period of time. If the system control is unable to regulate the power change appropriately, then the power overshoot phenomenon can occur, which is a condition when the system's output power exceeds a predetermined setpoint value before reaching a stable condition [4]. The phenomenon of power overshoot in renewable energy generation systems can cause various problems in the electric power system, especially in isolated electrical systems that have a relatively small generation capacity.

In systems with limited capacity, the power surge that occurs can affect the power balance of the system and trigger a disturbance in the power plant protection system. This condition can have an impact on the trip of other generating units connected to the same system and potentially cause system disruption to blackout [5]. Therefore, the regulation of the power limitation control system at solar power plants is one of the important aspects in maintaining the stability of the electric power system [6].

In order to understand the development of research related to the solar power system, especially in the aspects of power control, energy management, and electricity system stability, it is necessary to review the literature on relevant previous studies. This study aims to identify the approaches that have been used, the research focus that has been studied, and the main findings produced by each study. In addition, through this literature analysis, it can also be known that the research gap is the basis for the development of this research. A summary of relevant previous research is shown in Table 1.

In general, previous studies have shown that the application of solar power plants is able to improve system efficiency and reduce dependence on fossil fuel-based plants [7]. However, the integration of solar power into the electric power system also poses new challenges, especially related to power fluctuations due to variations in solar irradiation that can affect the stability of the system [8]. Therefore, further studies are needed on the control of solar power in dynamic conditions, especially in limiting production overshoot so as not to interfere with the electrical system, as is the focus of this study.

Table 1
Research review related to solar power control system and electrical system stability

Reference	Approach / Method	Research Focus	Main Findings
[9]	Solar PV performance analysis	Evaluation of on-grid solar PV performance	Solar PV improves the efficiency of the electrical system
[10]	IoT-based monitoring	Solar PV monitoring system	Monitoring improves data reliability and accuracy
[11]	SCADA system	Solar Power Control and Monitoring	SCADA makes it easier to control the solar PV system
[12]	Energy Management System (EMS)	Solar energy management	EMS is able to optimize energy distribution

[10]	System stability analysis	Integration of solar power plants into power systems	Solar power plants affect the stability of the electrical system
[11]	PID Controller	Control of the power output of the solar power	PID improves the system's response to load changes
[12]	Irradiation data analysis	The Influence of Weather on Solar Power Plants	Irradiation affects output power fluctuations
[13]	Isolated system case study	Implementation of solar power plants on the island	Solar PV effectively improves the efficiency of remote systems

Based on Table 1, it can be seen that research related to solar power systems generally focuses on improving system performance, monitoring implementation, and energy management through the Energy Management System (EMS). The application of technologies such as IoT and SCADA has been proven to increase operational reliability and simplify the system control process [14]. while the use of EMS plays a role in optimizing energy distribution in the power generation system [15]. On the other hand, the integration of solar power into the electrical system also has consequences for system stability due to power fluctuations affected by irradiation conditions [20]. This is relevant to the operational conditions of the Bawean PLTS which are integrated with PLTMG, where the contribution of power from PLTS as support internal load has the potential to cause system dynamics, especially when there is a rapid change in production. Therefore, further evaluation of the EMS-based power limitation control system at the Bawean Solar Power Plant is needed, especially in anticipation of production overshoot that can have an impact on the stability of the overall electrical system.

In modern solar power systems, the output power is usually regulated through an inverter controlled by the Energy Management System (EMS). EMS functions to regulate the interaction between renewable energy sources, energy storage systems, and conventional plants so that the system can operate optimally and stably [16]. System control generally uses a Proportional-Integral-Derivative (PID)-based control method to regulate the system's response to be able to achieve stable conditions quickly and minimize power overshoot [17].

Several studies have shown that the integration of renewable energy plants into isolated power systems requires more complex system control coordination than large interconnection systems. This is due to the relatively high sensitivity of the system to power changes so that even a small disturbance can have a significant impact on the stability of the electric power system [18]. Therefore, the proper implementation of an Energy Management System is an important factor in maintaining system stability when renewable energy plants are integrated with conventional plants [19].

Although various studies have discussed the integration of solar power in the electric power system, studies on the phenomenon of power overshoot in solar power systems that operate as a support for conventional power plants in isolated electricity systems are still relatively limited. In the Bawean Island electricity system, solar power plants are operated as additional plants that support the operation of PLTMG through the EMS control system that regulates the distribution of power between the solar power system, batteries, and system loads.

However, in its operation, there are still several disturbances related to the phenomenon of overshoot solar power production which has an impact on the stability of the electrical system. The power surge that occurs can affect the PLTMG auxiliary system so that the power plant trips and disrupt the operation of the electric power system as a whole. This condition shows that an evaluation of the performance of the power control system of solar power is very necessary to find out the cause of the overshoot and its impact on the stability of the electrical system [20].

Based on these problems, this study was conducted to evaluate the performance of the power control system for solar PV power limits against the phenomenon of production overshoot and its impact on the stability of the electricity system on Bawean Island as a support for PLTMG operations. The results of this study are expected to provide recommendations in optimizing the solar power control system so that the integration of renewable energy plants can run more stably and reliably on isolated electricity systems. The Bawean PLTS, which is one of the strategic program projects of the PLN corporation regarding renewable energy newness which is targeted at 23% by 2025, after the test and commissioning phases there are still obstacles in the operation process with the conditions of symptoms and impacts that occur as shown in Table 2.

Table 2
Disruption at Bawean solar power plant

Time of Occurrence	Description	Impact
January 21 at 11.00 WIB	There is an Overshoot Power Output of PLTS EMS 2 reaching 120 kW	- Trip di PLTMG Engine 2 - SDB Engine 2 Trip - Network hunting disorders
March 12 at 11.00 WIB	There was an overshoot of the power output of the EMS 3 solar power plant reaching 100 kW	- Fuse Auxiliary 3 putus, engine PLTMG 3 Ttrip - Cooling system PLTMG 3 trip - PLTMG 3 trip alarm charge temp maximum - Bawean electrical system blackout

2. Methodology

2.1 Research Flow and Control Strategy Framework

This study uses a structured workflow to evaluate the performance of the power limiting control system at Bawean PLTS through operational data analysis and system response testing. The research process begins with a literature study to identify relevant control approaches, system monitoring, and energy management methods in the solar power plant system and its integration with other plants. Furthermore, operational data obtained from monitoring systems such as EMS and iSolarCloud was collected, which included PLTS power parameters, PLTMG power, battery condition, and irradiation data. The next stage is the determination of the control strategy approach which is focused on the evaluation of the control system based on the Energy Management System (EMS), including power setpoint parameters, PID settings, and the protection system applied.

Furthermore, a data analysis process and system performance evaluation was carried out by observing the response to normal conditions and disturbances, especially those related to the phenomenon of power overshoot. A test of changing the power setpoint was also carried out to determine the system's response to dynamic operating conditions. The test results are then analyzed to assess the effectiveness of the control strategy in maintaining the stability of the electrical system. The final stage of this study is the preparation of recommendations for system control improvements to improve the performance and operational reliability of the Bawean Solar Power Plant. Overall, the flow of this research describes the integrated system control evaluation process as shown in Figure 1

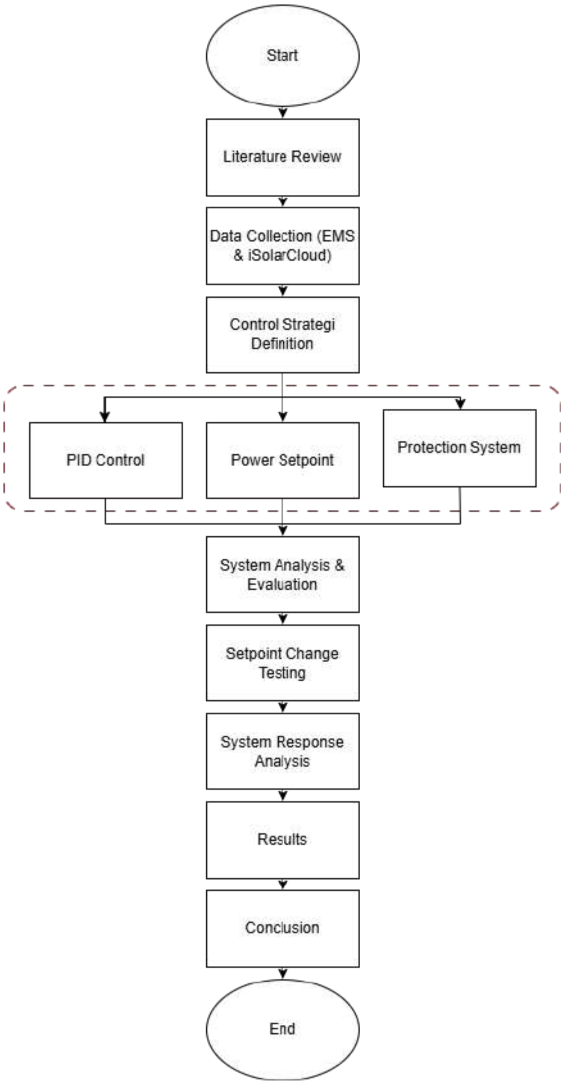

Fig. 1. Research methodology flowchart for evaluating the control system of PLTS Bawean

Tables 3, 4, and 5 present the main specifications of Bawean Solar Power Plants consisting of PV, inverter, and battery specifications. The Bawean PLTS system is designed with certain technical specifications that are tailored to the needs of the local electrical system so that it can operate optimally. The existence of solar PV not only aims to utilize the potential of solar energy, but also to improve the operational efficiency of the plant by reducing dependence on fossil fuels. Therefore, understanding the specifications and characteristics of the solar power plant system is important as a basis for evaluating the performance of the control system [21].

Table 3
PV specifications

Parameter	Specification
Maximum total capacity	408,240 kWp (tolerance +/- 1%)
Technology	Crystalline Sillicone (C-Si)
Net power	Maximum 403 kWp
Junction box	3 bypass diode
Cables	4 mm2 solar cable
Connector	MC4 (4 mm2)

Maximum system voltage	1000 Vdc/1500 Vdc
Manufacturing warranty	20 years of product, 25 years of performance
Standard	IEC 61215 / IEC 61646 / IEC 61730 / IEC 61701 / IEC 62716

Table 4
Inverter specification

Parameter	Specification
Inverter/PV capacity ratio	80% n/a 85%
Input (DC)	
Min. MPP Voltage	200 Vdc
Max. Input voltage	1000 Vdc/1100 Vdc
Output (AC)	
Rated power	100 kW
Max. AC apparent power	110 kVA
AC nominal voltage	380/400 V
AC grid frequency/range	50 Hz
Power factor range	0.8 leading, 0.8 lagging
THD	<= 3%

Table 5
Battery specifications

Parameter	Specification
Battery capacity	1.3 MWh (tolerance -3%)
Cycle	6000 (DOD 80%)
Depth of Discharge	90%
Efficiency	>95%
Authentication level	IEC 62619
PCS	3 × (75 s/d 100) kW
EMS	) d 300 kVA

2.2 Solar Power Control

Power control in the solar power system aims to maintain the stability of the output in accordance with the setpoint value determined by the Energy Management System (EMS). In this system, the power output of the solar power plant is affected by the solar irradiation conditions and the characteristics of the photovoltaic module. In general, the output power of solar PV can be expressed as the following equation (1) [22]:

$$P = \eta \cdot A \cdot G \tag{1}$$

Where is the output power (W), is the efficiency of the system, is the area of the panel (m2$P\eta A$), and is the intensity of solar radiation (W/G^{m2}).

In system control, the difference between the actual power and the setpoint is defined as an error, which can be expressed as the following equation (2) [23]:

$$e(t) = P_{set} - P_{actual} \tag{2}$$

This error value is used as the basis for control, one of which is through the PID (Proportional-Integral-Derivative) control, which is expressed as the following equation (3) [23]:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (3)$$

Where are the control signals, and each is a proportional, integral, and derivative constant.$u(t) K_p, K_i, K_d$

In addition, to evaluate the overshoot phenomenon, the overshoot percentage parameter is used which is formulated as the following equation (4) [23]:

$$M_p = \frac{P_{max} - P_{set}}{P_{set}} \times 100\% \quad (4)$$

This parameter indicates how much output power exceeds the predetermined setpoint value. A high overshoot value indicates that the control system is not optimal in responding to changes in operating conditions.

2.3 Study Location

The Bawean Solar Power Plant which is the object of study in this study is a solar energy generation facility owned by PT Pembangkitan Jawa Bali with an installed capacity of 406 kWp which is integrated with a battery system with a capacity of 1.3 MWh. This solar power plant is located on Jl. Pedoman No.10, Sungai Teluk Village, Sangkapura District, Bawean Island, Gresik Regency, and is geographically located at the coordinates of 5°46' S and 122°40' E. This system is built on an area of 2500 m2$\pm$ and is integrated with the Bawean PLTMG power plant unit with a capacity of 3×1 MW under the Gresik Power Generation Unit (UP). The construction of the solar power plant is carried out by PT PJB Services as an EPC contractor with the aim of supporting auxiliary power supply and improving the operational efficiency of the electricity system on Bawean island through the use of renewable energy. Figure 2 shows the location of the Bawean island solar power plant. Figure 3 shows the battery system in the battery compartment.

Fig. 2. Location of Bawean Island solar power plant

Fig. 3. Battery space

Figure 4 shows the Central Control Room (CCR) in the Bawean PLTS system which is placed as a control center separate from the field installation area, but remains in the same operational area with the PLTMG power plant unit. The CCR location is strategically designed to facilitate the process of monitoring and controlling the system as a whole through the Energy Management System (EMS), so that operators can monitor generation conditions, loads, and system responses in real-time. Meanwhile, Figure 5 shows the location of the inverter placed in a field area adjacent to the solar module array and protected by a canopy structure. This placement aims to minimize power losses and protect equipment from weather influences while facilitating the operation and maintenance process of the system.

Fig. 4. CCR room

Fig. 5. Inverter location

2.4 Bawean Solar System Design Review

Bawean PLTS is designed to be able to replace Auxiliary Power for engines 1, 2, and 3 in the commissioning phase setting, tuning, and power smoothing to be able to function as designed with the release power of the PV system and battery at a certain time to be able to supply power to each engine according to the parameters that have been determined. However, in the operation phase, it still requires further setting and tuning where as explained there is still an overshoot of power which results in operational disruptions of the Bawean Island electricity system which has an impact on electricity services to the community.

The Bawean PLTS design system consists of 3 PV systems with a battery system controlled by EMS (Energy) Management System) that supplies auxiliary power to each PLTMG engine as shown in Figure 6.

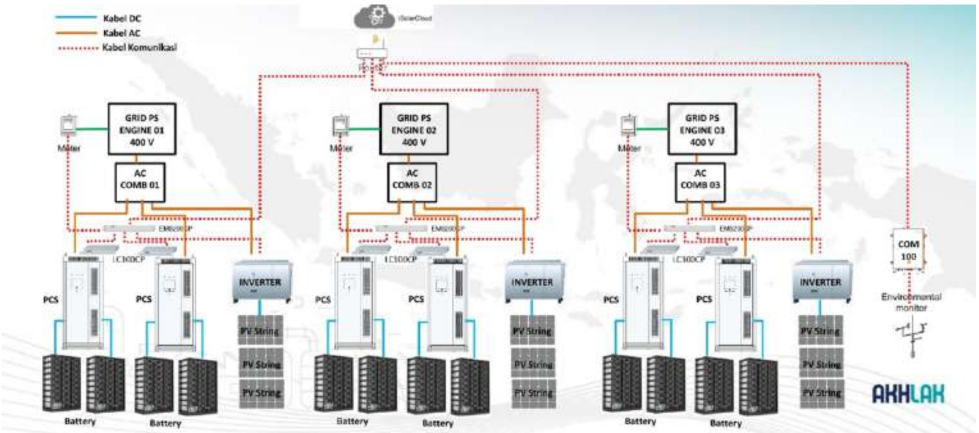

_**Fig. 6.** Bawean Island solar power plant design system

Figure 7 shows a detailed picture of each system and EMS setup where electrical energy is generated by photovoltaic (PV) modules which are then converted from direct current (DC) to alternating current (AC) through a solar inverter. The output power from the inverter is then combined into the air conditioner combiner before being fed to the load system. This system is also equipped with a Battery Energy Storage System (BESS) consisting of a battery, Battery Management Unit (BMU), Power Conversion System (PCS), and Local Control System (LCS) which functions to store electrical energy and maintain battery operating conditions. Several power meters are placed on the PV, grid, and load sides to monitor the power flow in the system. All of these components are controlled by the Energy Management System (EMS) which functions to regulate the limitation of solar PV output power, charging, battery discharge, and distribution of energy produced to supply auxiliary power needs in each PLTMG engine unit, so that system operations can run more efficiently and stably.

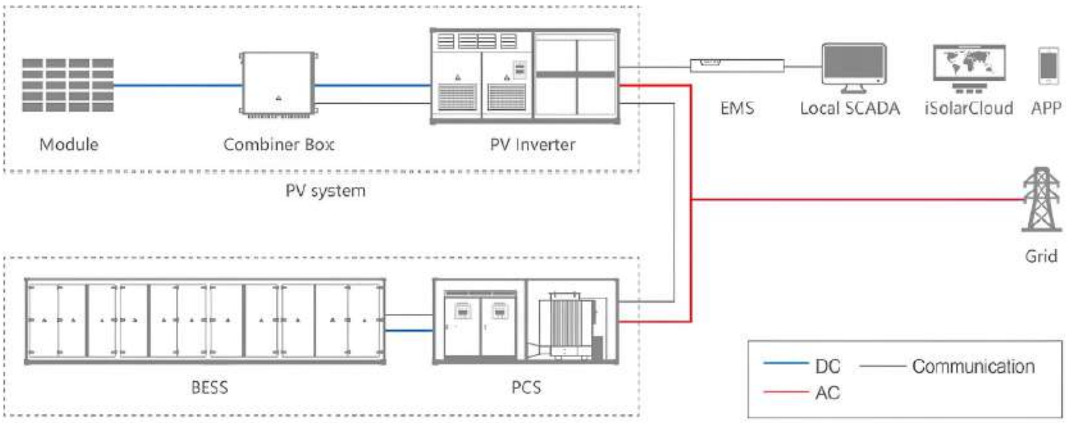

Fig. 7. Detailed design system for Bawean Island solar power plant control

3. Results

3.1 Fault Tree Diagram

The main cause of the PLTMG trip both at PLTMG unit 2 on January 21 and PLTMG unit 3 on March 12 was due to the overproduction of power from PLTS so that it hit the PLTMG auxiliary bus back. Figure 8 shows the root cause of the PLTMG trip due to the overshoot of solar PV power.

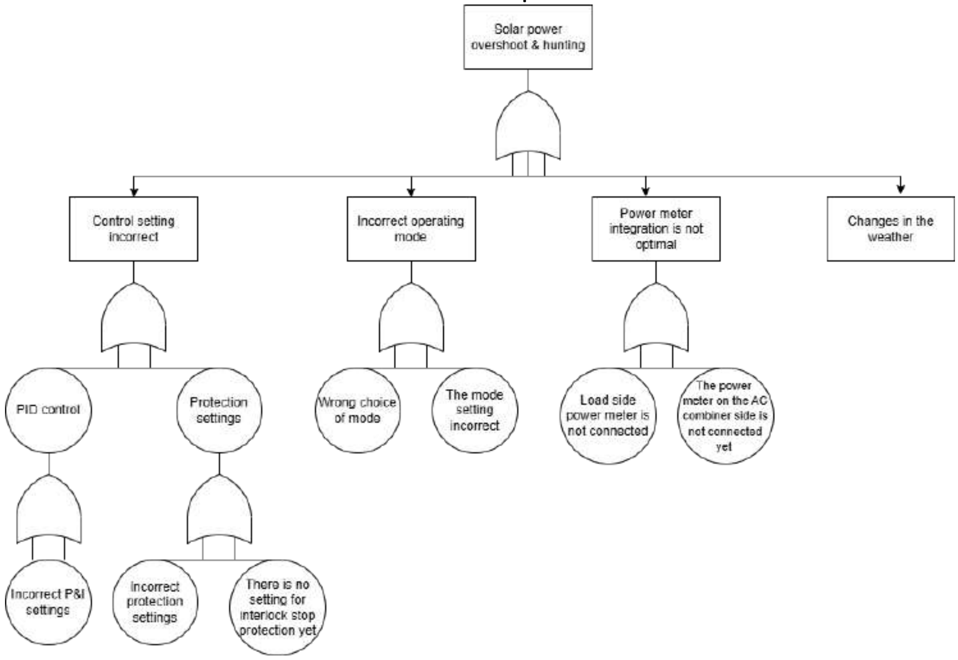

Fig. 8. Fault tree diagram trip PLTMG unit 2 and 3

The analysis of the Fault Tree Diagram shows that the main cause of power overshoot in solar PV comes from a suboptimal control system, especially in the setting of PID parameters, power setpoints, and protection systems. In addition, supporting factors such as system configuration mismatches also contribute. The impact of this condition is the disruption of the stability of the electrical system, which in some cases can trigger trips to the PLTMG and reduce the reliability of operations.

Figure 9 shows the root cause of the trip of PLTMG Unit 3. The cause of the overshoot of solar PV production power is the lack of precise EMS (Energy Management System) control settings that regulate PV and battery work. Several settings in the control system are the cause of the lack of optimal power control at solar power plants. One of them is the settings on the PID (Proportional-Integral-Derivative) control system which may not have been adjusted appropriately. Setting this parameter requires administrator login access that only Sungrow engineers have, so it cannot be done directly by the operator. In addition, the system protection setting is also not strict enough in limiting the power output of solar PV, so that it allows power production to exceed the set point. There is also a possibility that the interlock stop system has not been implemented in the EMS, so it is necessary to evaluate and plan for the addition of protection to improve the reliability of the system.

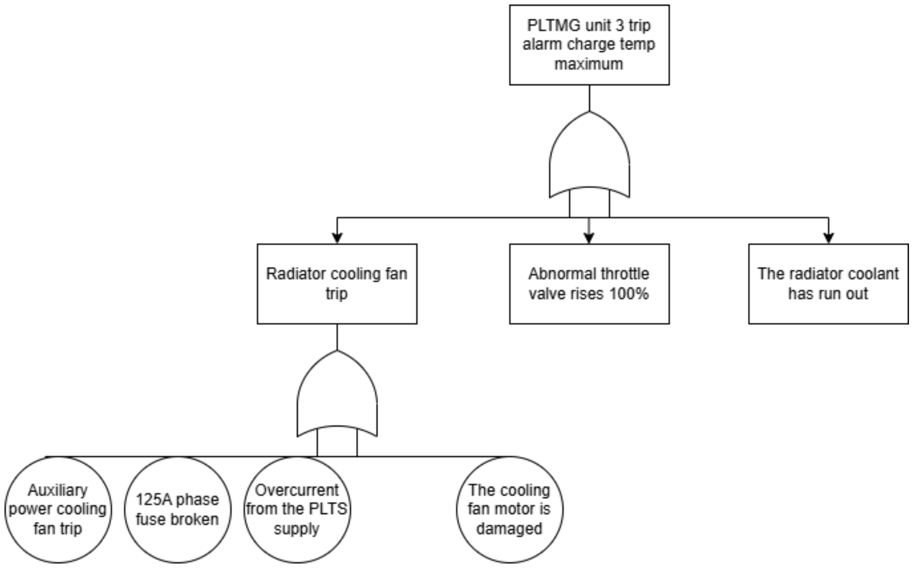

Fig. 9. Fault tree diagram trip PLTMG unit 3

3.2 Set Point Settings

The results of the setpoint change test showed that the system was not always able to follow the setpoint value stably. The main finding of this test is that the system response tends to be slow at the beginning, but is followed by a power surge that exceeds the setpoint value (overshoot). This condition shows that the control parameters used are not optimal in controlling the power transition. The impact on the system is an increased potential for operation instability, especially during rapid load changes or irradiation conditions. This has the potential to disrupt the coordination of operations between solar power plants and solar power plants

Trending operating data on EMS 1 during cloudy weather conditions on April 12 is shown in Figure 10. Based on the power curve graph displayed, it can be seen that the power generated by the PV system has fluctuated quite significantly. This condition is affected by unstable changes in solar irradiation due to cloud cover, causing PV power production to increase and decrease irregularly. In some periods, there is a sudden increase in power which is then followed by a decrease again when the intensity of solar radiation decreases. These fluctuations show that weather conditions have a direct influence on the stability of energy production from the solar power system. This trending data shows how the solar power system responds dynamically to changes in environmental conditions during cloudy weather periods.

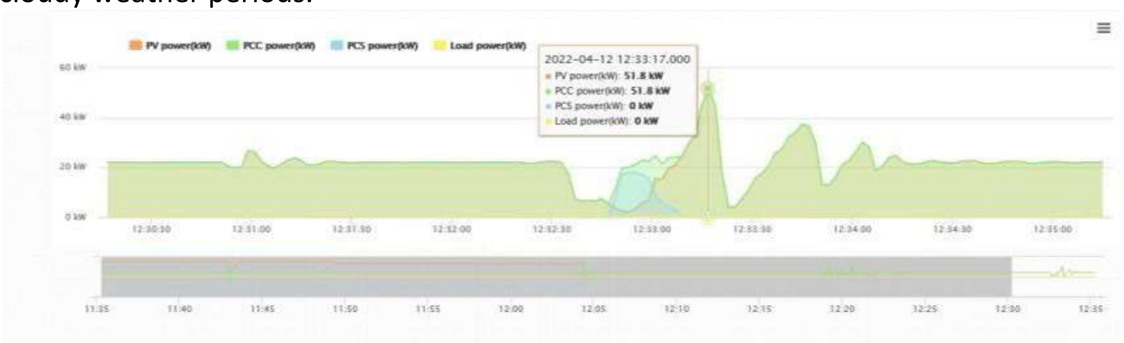

Fig. 10. Trending operations on April 12

Figure 11 shows that during cloudy weather conditions, there is a surge in solar power of 51.8 kW with a fixed setpoint of 20 kW. Power Returns to normal after 1 minute.

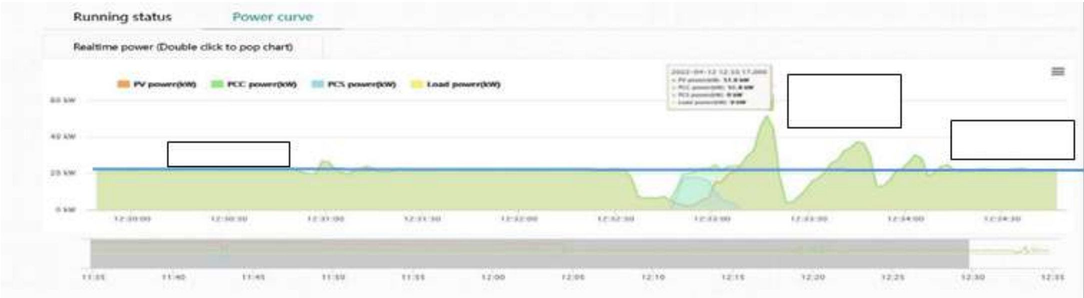

Fig. 11. Details of operating trends on April 12

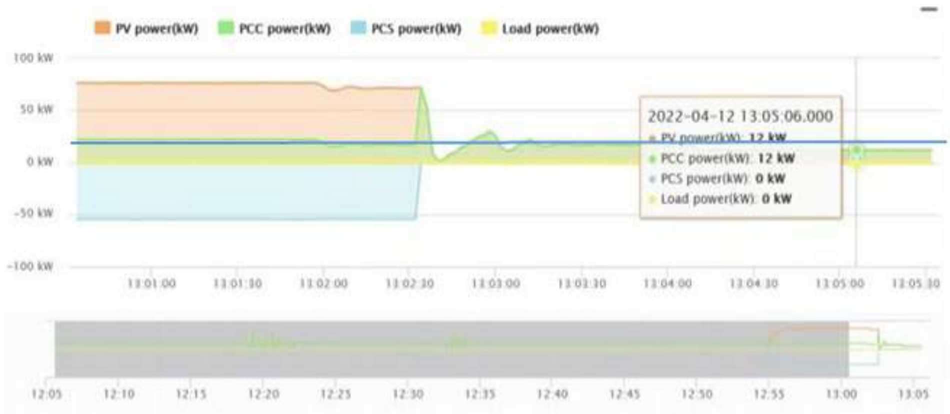

Fig. 12. Trial change of setpoint from 20 kW to 10 Kw

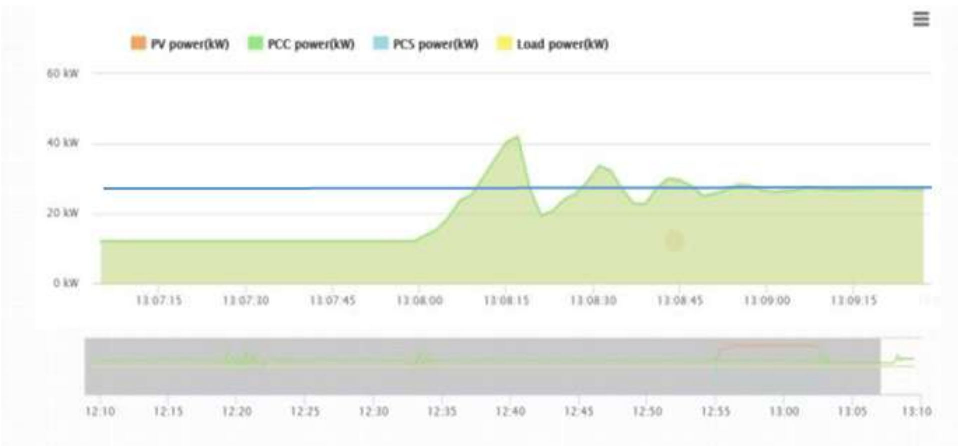

Fig. 13. Test change of setpoint from 10 kW to 25 kW

The trial was carried out by changing the power setpoint in the solar PV system to evaluate the response of the control system to changes in the power output limit. In the first test, the power setpoint was lowered from 20 kW to 10 kW shown in Figure 12, which aims to observe the system's ability to adjust the power output when the power limit is lowered. Furthermore, a second test was carried out by increasing the setpoint from 10 kW to 25 kW, shown in Figure 13 to see the system's response to the increase in the permissible power limit. The results of this test are used to evaluate the performance of the control system, especially in responding to setpoint changes and maintaining the stability of the power output of the solar PV.

From the trending during cloudy conditions and when the setpoint value changes shown in Figures 12 and 13 above, it can be concluded that the response of the solar power plant to the fixed setpoint value is not very good, as evidenced by the fact that there is still a large overshoot and the time to achieve the steady condition is still quite long, which is about 1 minute. It is necessary to re-tune so that the response obtained is not overshoot and quickly enough to reach a steady value.

3.3 Control System Evaluation

Based on the chronology of the incident, two disturbances occurred at almost the same time around 11.00 pm, when the photovoltaic (PV) system was in a state of maximum power production due to high solar irradiation. In this condition, it is suspected that there will be an increase in power production that exceeds the setpoint value, causing a power overshoot before the system stabilizes again. Rapid changes in irradiation can trigger power spikes in the inverter. If the response of the Energy Management System (EMS) in limiting power is not fast enough, this condition has the potential to affect the power balance in the Bawean Island electricity system integrated with PLTMG. Figures 14 and 15 show the trending operating parameters of the system at the time of a disruption in the Bawean PLTS system.

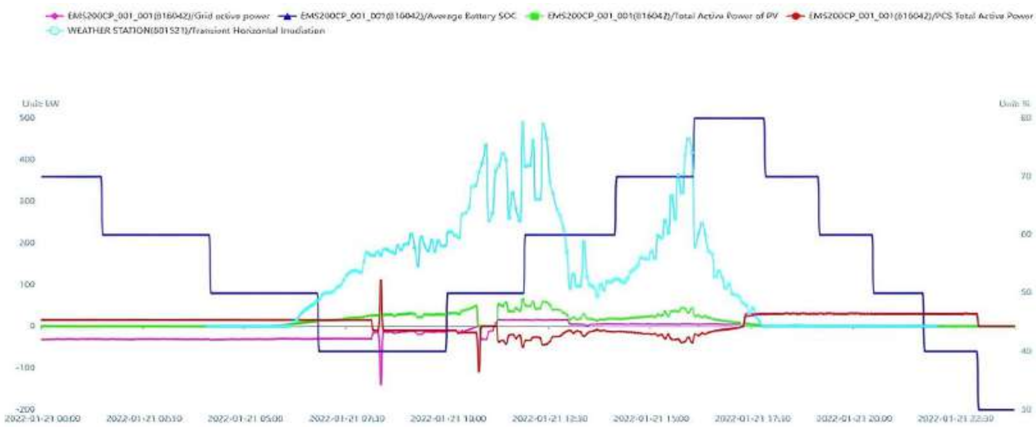

Fig. 14. Trending operation January 21st first case

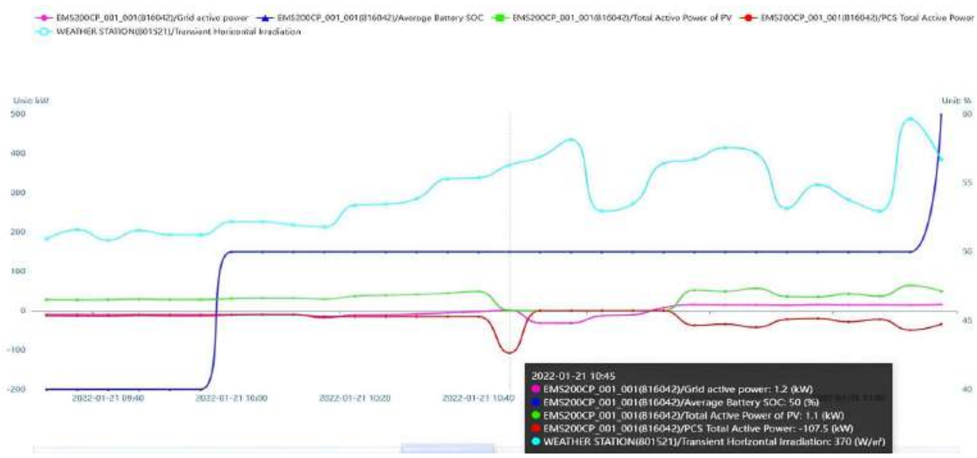

Fig. 15. Trending operation January 21st second case

The possibility of overcurrent is due to the fact that at 10.45 a.m. there was a PCS power surge of -107.5 kW where it was not clear whether the minus was charging or discharging due to a change in setting by the technician. iSolarCloud trend data with sampling data every 5 minutes maximum on January 21 is shown in Table 6.

Table 6
January 21 operating parameter data

Beat	PV Power	PCS Power	PLTD Power	SOC	Irradiance
10.45	1.1 kW	-107.5 kW	1.2 kW	50%	370 W/m2
10.55	0 kW	0 kW	-31.2 kW	50%	435 W/m2
11.00	0 kW	0 kW	-12.9 kW	50%	253 W/m2
11.10	0 kW	0 kW	7.7 kW	50%	471 W/m2

Figure 16 shows the trending data at the time of the March 12 outage showing the limitations of the monitoring data obtained from the iSolarCloud system. Based on the observation results, the trending data over time was not recorded completely so that some parameters of the system operation could not be displayed in their entirety. This condition is suspected to occur due to an internet network disruption that caused the process of sending data from the monitoring system to the iSolarCloud server to be temporarily interrupted. As a result, the available operational data records cannot comprehensively describe the condition of the system at the time of the outage.

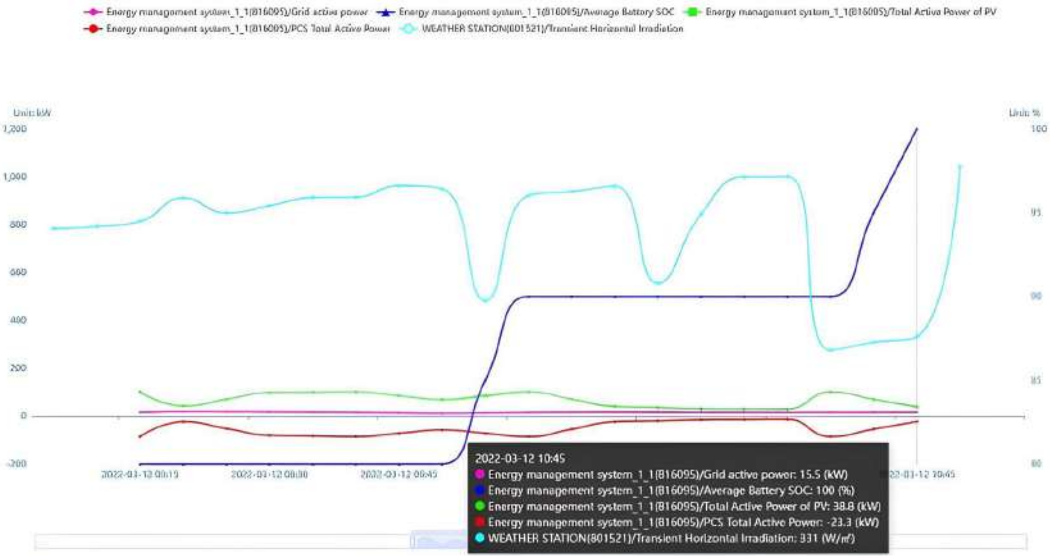

Fig. 16. Trending operations on March 12

There is a drastic decrease in PV power due to cloudy weather as seen from the irradiance value which suddenly drops drastically when the SOC of the battery is full, 100% so there is a possibility that when there is a transfer of power from PV to the battery, it causes an oversupply of power to the PS load. Data obtained 15 minutes before the incident is shown in Table 7.

Table 7
March 12 operating parameter data

Parameter	Value
PV Power	38.8 kW
PCS Power	-23.3 kW
PLTD Power	15.5 kW
SOC	100%
Irradiance	331 W/m2

3.4 Normalization Action Plan

Based on the results of the analysis, normalization steps were carried out through improving parameter control, adjusting setpoints, and strengthening the protection system. Key findings suggest that optimization of control and protection can reduce the potential for overshoot. The impact is to increase the stability of the system and the reliability of PLTS-PLTMG operations, so that the system can operate more safely and optimally.

Table 8 shows the normalization action plan prepared as a follow-up step to overcome the problem of power overshoot in the Bawean PLTS system. This Action Plan includes several improvement steps focused on evaluating and optimizing the control system as well as strengthening the protection system so that similar incidents do not recur. Through the implementation of this system control improvement, it is hoped that the solar power system can operate more stablely, be able to limit power output in accordance with the specified setpoint and maintain the reliability of the operation of the electrical system integrated with PLTMG.

Table 8
Normalization action plan

Equipment	Symptoms	Causes	Actions
EMS	Control overshoot response and long enough to reach a steady condition	Improper tuning control and protection	1. Tunning control EMS 2. Adds interlock stop protection in the event of an oversupply
MCB PLTS	No trips when the power is overcharged	MCB trip setting that is too high	Reducing the MCB PLTS trip setting to below the PLTMG bus trip setting

3.5 The Role of Solar Power Plants as a Support for PLTMG

The results of the analysis show that the integration of solar power plants makes a positive contribution to reducing the burden of self-use in the power generation system. The main finding of this result is a decrease in PLTMG fuel consumption in line with the increase in power contribution from solar PV. In addition, there is an increase in capacity factor in the overall power generation system. The impact on the system is increased operational efficiency and reduced exhaust emissions. However, this integration also requires good power control to maintain system stability.

The evaluation of the performance of the electricity system was carried out to determine the impact of the integration of the Bawean PLTS on the operation of the PLTMG as the main plant. This analysis includes a comparison of conditions before and after the operation of the solar power plant, especially on self-use, fuel consumption, carbon dioxide (CO_2) emissions, and the achievement of capacity factors. Prior to the existence of solar PV, power needs, including the cost of self-use, were fully supplied by PLTMG, so that fuel consumption and emissions were relatively higher and the value of the capacity factor tended to be stagnant. After the integration of solar PV, part of the consumption load itself can be met by solar energy, so that the PLTMG workload is reduced and has an impact on reducing fuel consumption and CO_2 emissions, as well as increasing the value of the capacity factor. A comparison of these conditions is presented in Table 9.

Table 9
Baseline performance and success of solar PV

Aspects	Before	After
Large self-usable power	The consumption load itself is supplied from PLTMG electricity production	Self-consumption load Partly supplied from solar PV
Amount of fuel required	A certain amount of PLTMG production power to the grid plus self-use load power	Reduced amount of power generated by solar PV
Carbon dioxide (CO_2) emissions	CO_2 emissions are as large as the production of PLTMG to the grid plus the load power of the self-use	Reduced amount of power generated by solar PV
Capacity factor achievement	CF stagnant	CF is on the rise

From Table 9 above, it shows that the existence of solar PV has a positive impact on the electricity system, characterized by reduced fuel needs and CO emissions$_2$, as well as increasing the value of PLTMG's capacity factor. In addition, some of the self-use load that was previously fully supplied by PLTMG can now be fulfilled by PLTS, thereby increasing the overall operational efficiency of the system.

Based on Figure 17, it can be seen that the capacity (CF) trend of PLTMG during the period from January 2021 to January 2022 shows the difference in performance before and after the integration of PLTS. In the period before solar PV operated, CF values tended to be in a relatively stable range without significant increases. This condition indicates that the performance of the plant is still completely dependent on the PLTMG, where part of the energy produced is used to meet the internal needs of the plant, thereby reducing the effectiveness of the power distribution to the system [24].

Fig. 17. CF PLTMG performance trend

After the implementation of solar PV with an on-grid scheme, there was a higher increase in CF values compared to the previous period. This increase shows that part of the internal load previously borne by PLTMG has been transferred to PLTS, so that the energy produced can be used more optimally. The integration of renewable energy plants in the logistics system is known to be able to improve the operational efficiency of conventional plants through reducing internal loads and optimizing power distribution [25].

Based on Figure 18, the trend of self-use (PS) of PLTMG shows a downward trend after the PLTS start operating. In pre-integration conditions, the PS value is relatively high because all internal power needs are still supplied by PLTMG, which has an impact on increasing fuel consumption and reducing the efficiency of the power generation system [26]. After the solar power plant is operational, the PS value decreases gradually, indicating that some of the internal power needs have been met by the solar power plant, thereby reducing the workload of the main plant.

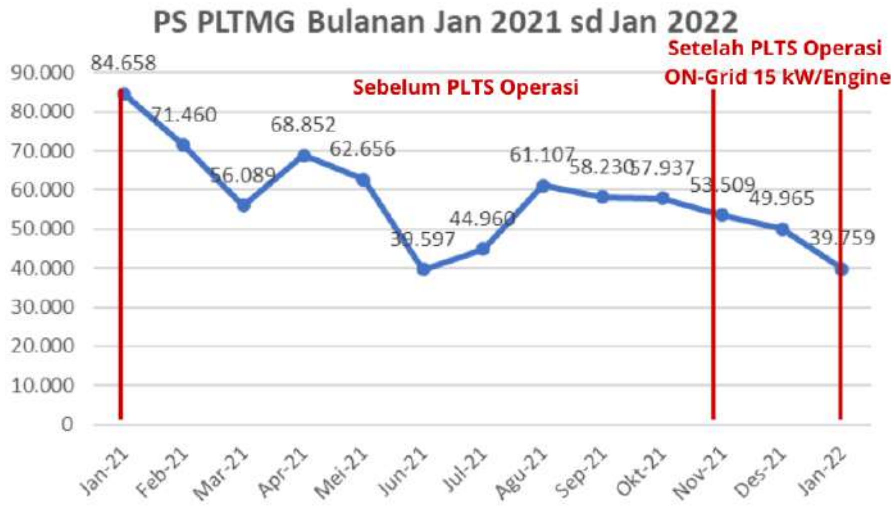

Fig. 18. Self-use before and after the solar PV operation

This decrease in self-use is in line with the concept of using solar energy as an auxiliary supply, where solar power is used to supply internal loads and increase the efficiency of the overall power generation system. With reduced internal loads, PLTMG can operate more optimally, which is reflected in the increase in the value of the capacity factor. The relationship between the reduction in PS and the increase in CF strengthens that the integration of Bawean Solar Power Plants makes a positive contribution to increasing efficiency, reducing fuel consumption, and reducing emissions in the electricity system [26].

4. Conclusion

The results of the evaluation of the Bawean solar power plant system integrated with the PLTMG showed that the increase in output power occurred significantly during the peak production period, especially around 11.00. This condition causes the system response to be critical when the power produced by the solar power cannot be controlled according to the predetermined setpoint. Further analysis showed that the control system, especially the Energy Management System (EMS), was not able to respond quickly and accurately to power changes, resulting in production overshoot that exceeded the permitted operating limit. In addition, the control parameter settings that are not optimal and the protection configuration that is not strict enough also increase the potential for interference in the system.

Thus, it can be concluded that the main problem in the Bawean PLTS lies in the performance of the control and protection system that is not optimal in limiting the output power. This condition has a direct impact on the stability of PLTMG operations as the main plant, and even has the potential to cause trips to the system. Therefore, optimization is needed in control settings, increased EMS system response, and strengthening the protection system to ensure that solar power plants can operate stably and be well integrated in the Bawean Island electricity system.

As a continuation, further research is recommended to optimize system control parameters more deeply, especially in PID settings, power setpoints, and Energy Management System (EMS) coordination so that the system's response to changes in operating conditions becomes more stable. In addition, the development of a more comprehensive simulation model is also needed to analyze the interaction between solar PV, energy storage systems, and solar power plants in various operating scenarios. The use of long-term operational data and the exploration of more adaptive control methods are expected to improve the accuracy of the analysis, while supporting the improvement of the efficiency, reliability, and stability of the overall electrical system

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