Rotor Angle Analysis on Power Proportion in Generator and Photovoltaic Hybrid Low Voltage System

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Abstract— Electrical energy is essential in modern society, and with the growing demand, all available energy resources are being utilized to meet this need. Insufficient planning and calculation in energy provision can affect the stability of electricity generated by power plants, especially in low-voltage microsystems directly connected to loads. This study investigates the behavior of synchronous microgenerators and photovoltaic systems, focusing on the rotor angle of the generator. Changes in the photovoltaic contribution can cause shifts in the generator's rotor angle, necessitating an analysis of these shifts. An experimental method was used to measure and analyze the power distribution by recording current and voltage in a micro synchronous generator and a grid-tie inverter under a 300-watt linear load. The results show that the generator's rotor angle remains stable and the grid-tie inverter remains synchronized, with an average angle of 40.2° at a photovoltaic contribution of 32.26% and a synchronous microgenerator contribution of 67.74%. However, when the photovoltaic supply exceeds 37.00%, the rotor angle shifts further, leading to a loss of synchronization in the grid-tie inverter. Additionally, irradiance was found to have a linear effect on photovoltaic distribution. The findings of this study contribute to a better understanding of rotor angle behavior and grid synchronization, providing insights for the development of more reliable and efficient renewable energy systems that maintain electrical stability in low-voltage applications.

Keywords— Electrical systems; generator rotor angle; hybrid electric power proportion; micro generator; photovoltaic.

I. INTRODUCTION

In the modern era, the reliability and stability of electric power are crucial factors in maintaining the overall stability of the electrical power system. Advances in power generation technology have enabled the use of renewable energy sources, such as synchronous micro-generators and photovoltaic grid inverters, as alternatives to reduce dependence on finite fossil fuels and mitigate environmental damage. However, with the increased adoption of these generation systems, it is essential to gain a deeper understanding of how their behavior affects the stability of electrical power [1]-[4].

Electrical power quality refers to the degree to which the voltage, frequency, and electrical waveform supplied to a device remain stable and free from disturbances that could impair the device's performance or cause damage [5]-[7]. Previous research primarily concentrated on power quality and harmonic distortion, overlooking the influence of photovoltaics. However, photovoltaics indirectly affect the stability and power quality in hybrid systems. Synchronous generator microgeneration systems and photovoltaic grid-tied inverters exhibit complex properties and dynamic interactions with the power grid. Therefore, it is essential to identify and analyze the impact of these generation systems on the stability of electrical power [8], [9].

A synchronous microgenerator is a type of generator designed for small-scale applications. This system possesses synchronization characteristics that influence the stability of both frequency and voltage within the network. [10]. On the other hand, photovoltaic grid inverters convert solar energy into electricity and feed it into the distribution network. However, fluctuations in the solar energy input can impact the stability of electrical power. It would be highly interesting to examine the effects of combining two energy sources with different characteristics, such as synchronous microgenerators and photovoltaic systems, to supply the load and assess how their interaction influences power stability. [10]-12].

Research on hybrid energy systems has been explored extensively, with a focus on various renewable energy sources and their integration into power grids. Previous studies have examined Solar Power Plants, highlighting their use as renewable energy sources that either charge batteries in off-grid systems or feed excess energy into the grid in on-grid systems. The performance of grid-tie inverters, which convert solar energy and feed it into the distribution network, is influenced by solar radiation, affecting power output, power factor, and efficiency. High solar radiation typically improves efficiency, but grid-tie inverters can exhibit distorted current waveforms with ripple noise, potentially causing high harmonics and lower efficiency [13], [14].

Other research has evaluated photovoltaic-diesel hybrid systems, focusing on their energy, environmental, financial, and economic impacts in regions with unstable electric grids, such as Palestine, Lebanon, and Iraq. This study considered various fuel tariff scenarios, capital costs, and environmental factors [7], [15].

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Concerns about power quality have also been addressed due to the increasing use of inverter-based power distribution resources. These systems can introduce voltage imbalances, harmonic distortions, and long-term voltage variations. Analyzing the power quality of distribution systems, considering the impact of inverter outputs and the allocation of distribution plants and batteries, is crucial [16], [17].

Additionally, a study at the University of Muhammadiyah Makassar investigated an on-grid power generation system without battery storage. This research demonstrated that on-grid systems could save electricity costs by sharing power with the national grid and recommended using Exim kW-h to monitor energy exports [18], [19].

While previous research provides a foundation, there is a gap in understanding the influence of rotor angle on small-scale renewable energy systems using inverters. This study aims to explore how photovoltaic distribution affects rotor angle shifts in synchronous generators and their impact on system stability. By focusing on the relationship between power proportions and rotor angle through direct experimental measurements, this research seeks to fill this gap and offer insights for developing hybrid photovoltaic and micro-generator systems, particularly in Indonesia's diverse island context. The goal is to achieve self-sufficient energy availability on each island.

The purpose of this study is to analyze the behavior of synchronous and photovoltaic microgenerator generation systems and determine how much impact the proportion of photovoltaic distribution has on the shift of rotor angle in the generator. This is to find out the extent to which photovoltaics affect the rotor angle and the stability of the synchronous generator in the stability of the hybrid system.

The structure of this paper is organized as follows. After the discussion in this section, the research methodology utilized in this paper is elaborated in section 2. It includes the design of scenarios illustrating the problem, the implementation of the proposed clustering method, performance analysis of the parameters and models, as well as a description of the defined simulation parameters. Section 3 presents the outcomes of the simulations that have been conducted and provides a discussion of them. Finally, section 4 concludes the paper.

II. METHOD

Figure 1. Describe the stages of the research. The research process began with a comprehensive Literature Study, which included examining references related to the reliability parameters of electrical systems, load calculations, analysis methods, and the design of Solar Power Plants. This stage also reviewed sources related to microgenerator calculations, establishing a solid foundation for understanding the research context.

The next stage, Secondary Data Collection, involved gathering Datasheet for Grid Tie Inverters, 1-phase DC motors, Synchronous Micro Generators, and Photovoltaics. This data was crucial for designing and implementing the system.

Following data collection, the research moved to the System Design phase. This included creating and defining the specifications for the Solar and Micro Synchronous Generator systems, determining the specifications for the 1-phase drive motor and synchronous microgenerator, and considering the necessary protection design for the system.

The final stage was Implementation, where the design was put into practice according to the specified requirements. This involved setting up the photovoltaics, 1-phase DC motors, and microgenerators according to their specifications.

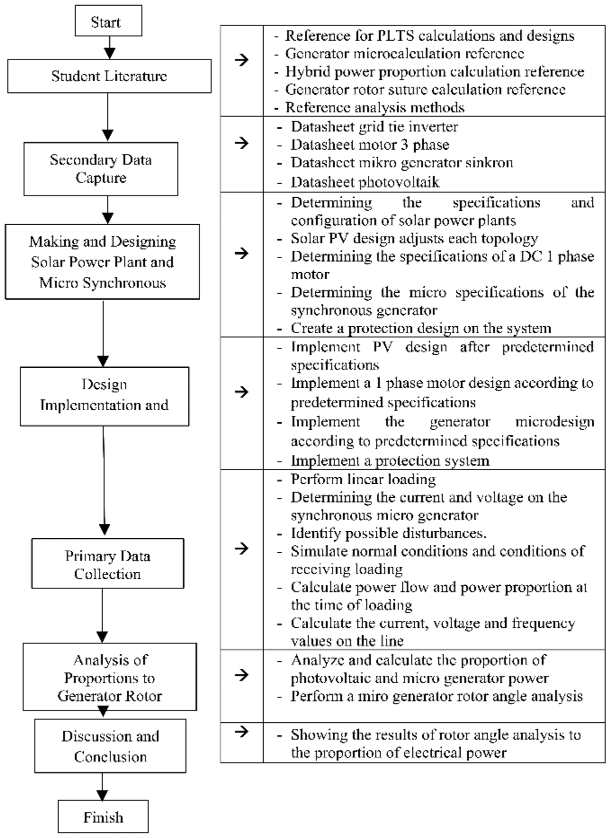

Figure 1. Research Flow Diagram

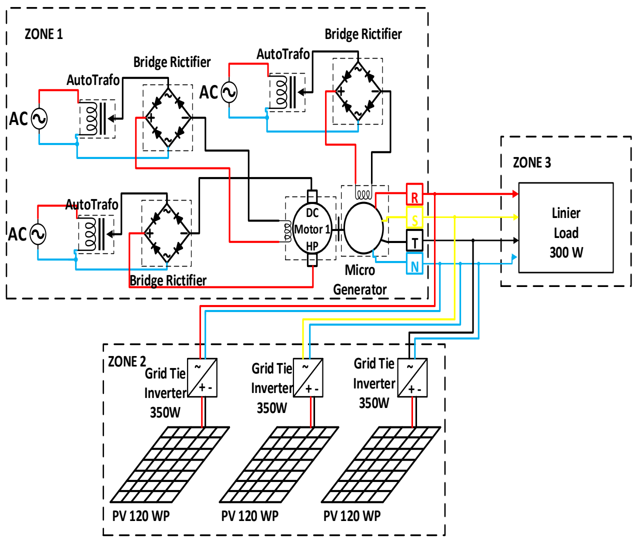

Figure 2. Test Series

Figure 2. illustrates the pre-designed working drawings, which include a setup featuring a 1-phase DC motor and a microgenerator connected to the output of a Grid Tie Inverter. This system is also connected to a 300-watt linear load. An AC source provides the necessary electrical energy, while an autotransformer adjusts the AC voltage to a desired level. A bridge rectifier is used to convert AC voltage to DC voltage, and the Grid Tie Inverter converts the DC voltage back to AC voltage, ensuring synchronization with the waves emitted by the microgenerator.

The subsequent step involves retrieving data on the proportion of linear loading power within the system. During this phase, the current and voltage of the synchronous and photovoltaic microgenerators will be measured, and any potential disturbances will be identified. Simulations will be conducted under both normal and load conditions to calculate the power flow based on the design specifications, current values, and voltage levels on the line.

A. Rotor Angle Calculation

Rotor angle stability refers to the capability of synchronous machines within a power system to maintain proper alignment. When two synchronous generators work in parallel to supply active power to a load, the distribution of this load is influenced by the rotor angles of the generators. It is crucial to ensure that these values align with the corresponding formulae [1], [20], [21].

The formula to determine the value of If, where Ea_1 represents the voltage at If (V) and Ia1 represents the current at If (A), is given by:

$$If = \frac{Ea_1}{Ia_1} \quad (1)$$

To find If, Based on the calculations, If is 956.64, serving as the reference base for the exponential function, while If saturation is 646.79, acting as the reference value for saturation. The next step is to determine L to find L_1, using the formula:

$$L_1 = \sqrt{\frac{{If_1}^2 - r^2}{2\pi f}} \quad (2)$$

Here, r is the resistance of the coil in the generator's r-axis, measured manually as 12.7 Ω, and f is the generator's frequency, set at 50 Hz. Once L1 is determined, find X_1using:

$$X_1 = 2.\pi.f.L_1 \quad (3)$$

With X_1 known, calculate E for exponential E_1 and E_4 for saturation using:

$$E_1 = V_t + \left(I_{ag}.(ra + X_1.i)\right) \quad (4)$$

Here, Vt is the generator voltage (V), I_{ag} is the excitation current (A), X_1 is the impedance with the coil resistance and inductance (Ω), and rarara is the resistance of the single-phase coil (Ω). After determining E_1 and E_4, convert the imaginary numbers into polar form using:

$$Magnitude\ E_1 = |E_1| \quad (5)$$

Convert the polar form into radian degrees:

$$Deg\ E\ rad = arg(E_1) \quad (6)$$

Finally, convert the radian value into degrees:

$$Deg\ E\ deg = arg(E_1)\left(\frac{180}{\pi}\right) \quad (7)$$

The final analysis involves examining the power proportion and the rotor angle of the generator. These results help in understanding the rotor angle shifts in the electrical energy produced by the designed and implemented system.

III. Results and Discussion

A. The results of testing and measuring the current and voltage of generators and photovoltaics.

Tables II and III provide essential data for the analysis of rotor angles by presenting the output voltages and currents from micro-generators, photovoltaics, and loads, respectively. This data, along with the generator voltage, output current, photovoltaic data, and total load information, is crucial for understanding the system's behavior and analyzing the power system's performance.

The hybrid test between micro-generators and photovoltaics involved measuring voltages and currents at 30-minute intervals from 9:00 a.m. to 3:00 p.m. Each test was conducted under stable weather conditions, maintaining an average solar radiation of approximately 1500 W/m². Accurate voltage readings were ensured using a well-calibrated multimeter. This meticulous approach aimed to ensure the reliability of the data, providing a robust foundation for analyzing the hybrid system's interactions and performance characteristics.

The measurements detailed in Tables I and II are integral for evaluating the generator angle. By utilizing data from the generator output current, photovoltaic systems, and load, alongside the generator's output voltage and load data, the performance of the generators under various operating conditions and load scenarios can be assessed. This data is crucial for understanding the dynamic behavior of generator angles and optimizing system operation to maintain stability and reliability in power supply.

Figure 3 displays the accumulated real-time measurement data from 9:00 a.m. to 3:00 p.m., using a linear load in the form of a 300-watt incandescent lamp. The excitation current set to 0.8 A, corresponding to the generator's peak capability. The measurements were conducted in sunny weather with solar radiation exceeding 1500 W/m² and humidity below 50%. These optimal conditions were chosen to ensure the accuracy and reliability of the data. Any lapse in precision during data collection could impact the results, highlighting the importance of careful and accurate measurement procedures to avoid compromising the study's integrity.

TABLE I. Results of Generator Set, Photovoltaic, and Load Voltage Measurements

Hour	Voltage (V)								
	R			S			T		
	Generator	Inverter	Carry	Generator	Inverter	Carry	Generator	Inverter	Carry
09:00	252.1	251.1	251.6	259.1	250.3	254.7	251.7	249.1	250.4
09:30	251.1	253.6	252.4	253.6	251.4	252.5	254.7	256.7	255.7
10:00	254.1	258.1	256.1	257.3	254.3	255.8	254.3	251.1	252.7
10:30	257.3	251.1	254.2	260.1	247.1	253.6	259.3	250.1	254.7
11:00	247.9	252.3	250.1	259.1	260.1	259.6	260.1	259.7	259.9
11:30	247.4	250.8	249.1	254.6	250.3	252.5	251.1	255.7	253.4
12:00	252.3	249.1	250.7	253.1	250.3	251.7	252.1	254.1	253.1
12:30	251.5	248.2	249.9	246.7	242.7	244.7	252.5	248.2	250.4
13:00	249.7	248.6	249.2	250.2	242.3	246.3	252.1	243.8	248.0
13:30	254	249.5	251.8	243.4	244.1	243.8	244	241.1	242.6
14:00	246.6	247.7	247.2	245.5	249.3	247.4	251.9	245	248.5
14:30	253.1	258.1	255.6	249.8	251.1	250.5	249.1	241.1	245.1
15:00	251.1	244.1	247.6	243.3	239.1	241.2	243.3	249.1	246.2

TABLE II. RESULTS OF GENERATOR CURRENT, PHOTOVOLTAIC, AND LOAD MEASUREMENT

Hour	Current (A)								
	R			S			T		
	Generator	Inverter	Carry	Generator	Inverter	Carry	Generator	Inverter	Carry
09:00	0.53	0.15	0.68	0.41	0.14	0.55	0.51	0.16	0.67
09:30	0.41	0.22	0.63	0.45	0.27	0.72	0.49	0.16	0.65
10:00	0.38	0.16	0.54	0.44	0.22	0.66	0.43	0.17	0.6
10:30	0.42	0.2	0.62	0.48	0.28	0.76	0.51	0.19	0.7
11:00	0.39	0.18	0.57	0.4	0.3	0.70	0.42	0.23	0.65
11:30	0.5	0.16	0.66	0.51	0.18	0.69	0.49	0.17	0.66
12:00	0.51	0.24	0.75	0.51	0.24	0.75	0.51	0.25	0.76
12:30	0.5	0.24	0.74	0.48	0.28	0.76	0.49	0.19	0.68
13:00	0.52	0.16	0.68	0.42	0.26	0.68	0.39	0.2	0.59
13:30	0.52	0.17	0.69	0.43	0.25	0.68	0.39	0.25	0.64
14:00	0.52	0.16	0.68	0.51	0.25	0.76	0.41	0.25	0.66
14:30	0.52	0.17	0.69	0.5	0.24	0.74	0.41	0.14	0.55
15:00	0.51	0.14	0.65	0.52	0.14	0.66	0.4	0.13	0.53

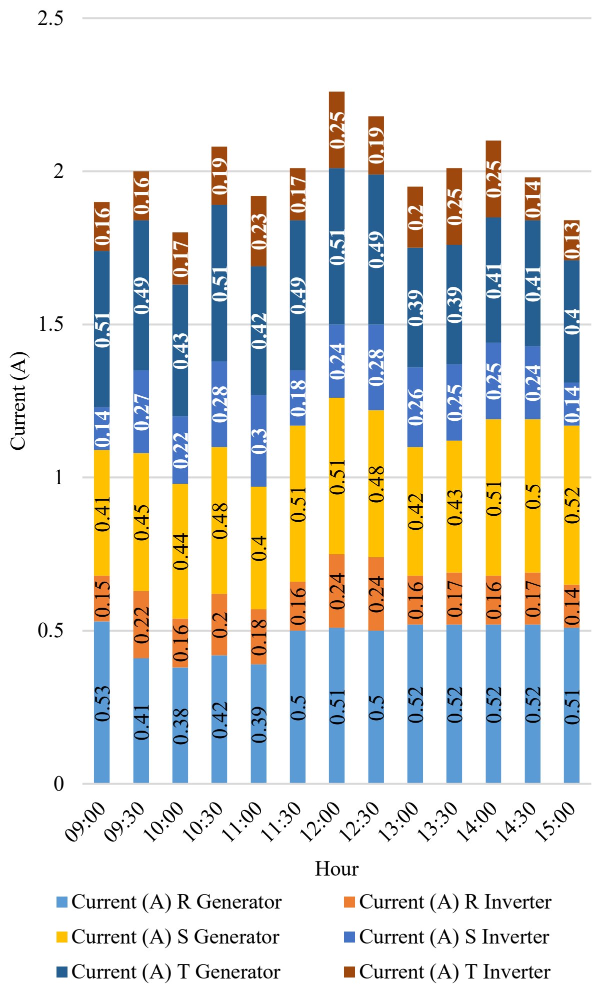

Figure 3. Generator and Photovoltaic Total Current Diagram

In this study, hybrid output voltage and current data from generators, photovoltaics, and loads were collected and compiled into Table I and Table II. This data provides a detailed view of power distribution within the hybrid system. To calculate the proportion of power generated by each component, a percentage method was used, where the total current of the generator and photovoltaic components was divided by each phase's current and multiplied by 100% for each hybrid output. The results of these calculations are recorded in Table IV. This approach determines the contribution of each component to the overall power generated by the system.

The data in Table IV consists of proportional values obtained per hour. To simplify analysis, these proportional values were averaged and are illustrated in Figure 4. The graphical representation helps to provide a clear and accessible visualization of each component's relative contribution to the total power of the hybrid system. These data processing steps enhance the understanding and interpretation of the results, presenting a more comprehensive overview of the system's performance.

TABLE III. PROPORTION MEASUREMENT RESULTS

Hour	Power Proportion (%)								
	R			S			T		
	Generator	Inverter	Carry	Generator	Inverter	Carry	Generator	Inverter	Carry
09:00	25.98	7.35	33.33	24.85	8.48	33.33	25.37	7.96	33.33
09:30	21.69	11.64	33.33	20.83	12.50	33.33	25.13	8.21	33.33
10:00	23.46	9.88	33.33	22.22	11.11	33.33	23.89	9.44	33.33
10:30	22.58	10.75	33.33	21.05	12.28	33.33	24.29	9.05	33.33
11:00	22.81	10.53	33.33	19.05	14.29	33.33	21.54	11.79	33.33
11:30	25.25	8.08	33.33	24.64	8.70	33.33	24.75	8.59	33.33
12:00	22.67	10.67	33.33	22.67	10.67	33.33	22.37	10.96	33.33
12:30	22.52	10.81	33.33	21.05	12.28	33.33	24.02	9.31	33.33
13:00	25.49	7.84	33.33	20.59	12.75	33.33	22.03	11.30	33.33
13:30	25.12	8.21	33.33	21.08	12.25	33.33	20.31	13.02	33.33
14:00	25.49	7.84	33.33	22.37	10.96	33.33	20.71	12.63	33.33
14:30	25.12	8.21	33.33	22.52	10.81	33.33	24.85	8.48	33.33
15:00	26.15	7.18	33.33	26.26	7.07	33.33	25.16	8.18	33.33

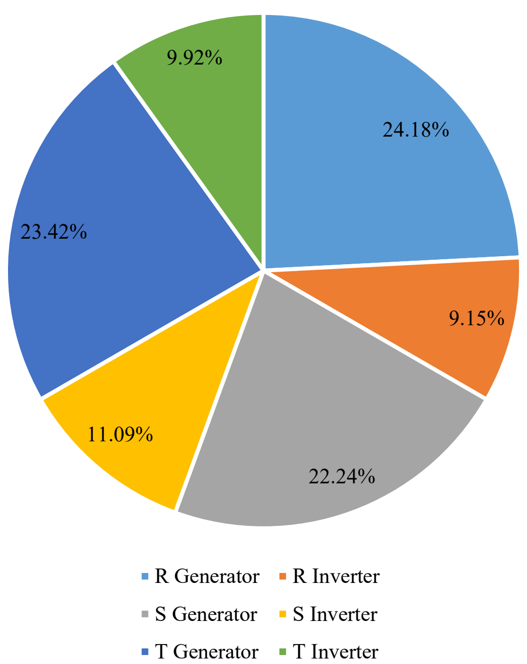

Figure 4. Photovoltaic Power Dependency Generator and Diagram

B. Generator Set Testing Obtained Micro Synchronous Generator Set Characteristics

Testing a generator is crucial for obtaining characteristic reference data, especially when datasheets may not provide complete information. By examining the values of If1, If2, If3, If4, If5, and If6, we can assess the generator's performance, including peak performance and operational conditions. This data is essential for calculating the phasor angle in the generator and for a comprehensive understanding of micro-synchronous generators.

The testing process involves several short-circuit steps at different stages to evaluate the generator's performance. The results of these tests are recorded in Table IV.

In Figure 5, points If1, If2, and If3 represent the dynamic conditions of the phase current within the system. Conversely, points If4, If5, and If6 denote steady-state conditions, serving as reference points for determining the exact phasor angle value. By using these reference points, we can accurately calculate the phase angle, which aids in analyzing and understanding the current phase conditions, particularly regarding the system's dynamic and stable responses.

TABLE IV. GENERATOR CHARACTERISTIC DATA RESULTS

Excitation Current (A)	Close Circuit Current (mA)	Open Circuit Voltage (V)
0	0	10
0.02	0	25
0.04	3.34	29
0.06	16.67	42
0.08	30.00	57
0.10	43.33	72
0.12	56.67	81
0.14	69.99	92
0.16	83.33	103
0.18	96.66	115
0.20	109.99	129
0.22	123.33	137
0.24	136.66	145
0.26	149.99	152
0.28	163.33	161
0.30	176.66	169
0.32	189.99	177
0.34	203.33	179
0.36	216.66	183
0.38	229.99	194
0.40	243.33	199
0.42	256.66	205
0.44	269.99	209
0.46	283.33	213
0.48	296.66	219
0.50	309.99	220
0.52	323.33	225
0.54	336.66	229
0.56	349.99	231
0.58	363.33	235
0.60	376.66	239
0.62	389.99	240
0.64	403.33	241
0.66	416.66	242
0.68	429.99	243
0.70	443.33	245
0.72	456.66	247
0.74	469.99	248
0.76	483.33	249
0.78	496.66	249
0.80	509.99	250

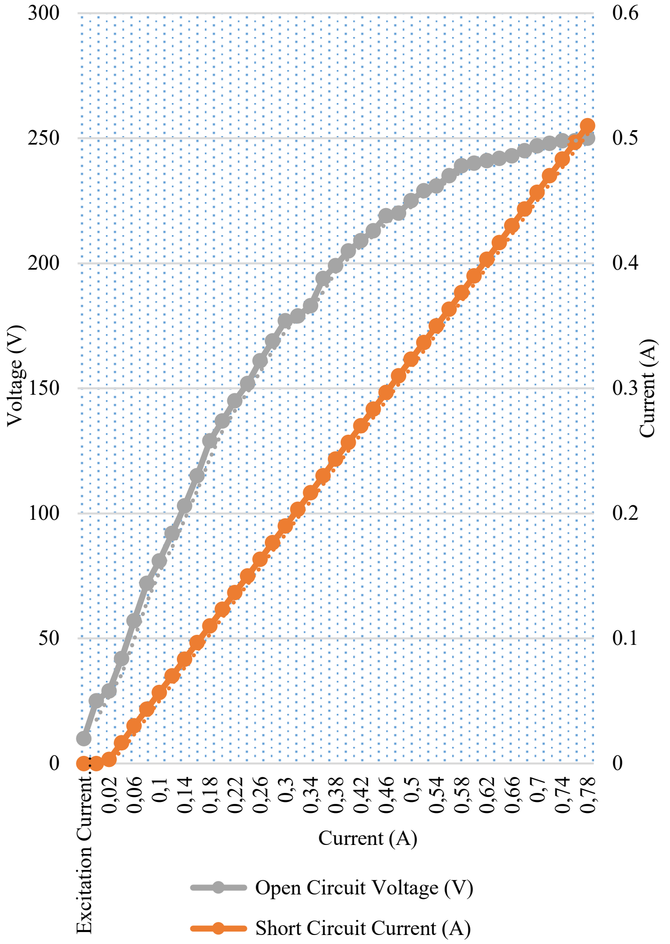

Figure 5. Diagram of Micro Generator Characteristics

TABLE V. RESULTS OF ANGULAR CALCULATION ANALYSIS WITH R-PHASE PROPORTION

Hour	Phase R				
	Generator Power (W)	**Inverter Power (W)**	**Generat-or Proport-ion (%)**	**Inverter Propor-tion (%)**	**Rotor Angle (°)**
09:00	131,23	37,14	77,94	22,06	49,37
09:30	105,00	56,34	65,08	34,92	48,44
10:00	95,61	40,26	70,37	29,63	48,93
10:30	106,76	50,84	67,74	32,26	48,64
11:00	98,18	45,32	68,42	31,58	48,91
11:30	124,93	39,98	75,76	24,24	49,12
12:00	128,70	60,56	68,00	32,00	48,85
12:30	127,80	61,34	67,57	32,43	48,49
13:00	129,56	39,86	76,47	23,53	49,20
13:30	130,16	42,55	75,36	24,64	49,07
14:00	129,53	39,86	76,47	23,53	49,21
14:30	130,21	42,57	75,36	24,64	49,06
15:00	126,05	34,60	78,46	21,54	49,42

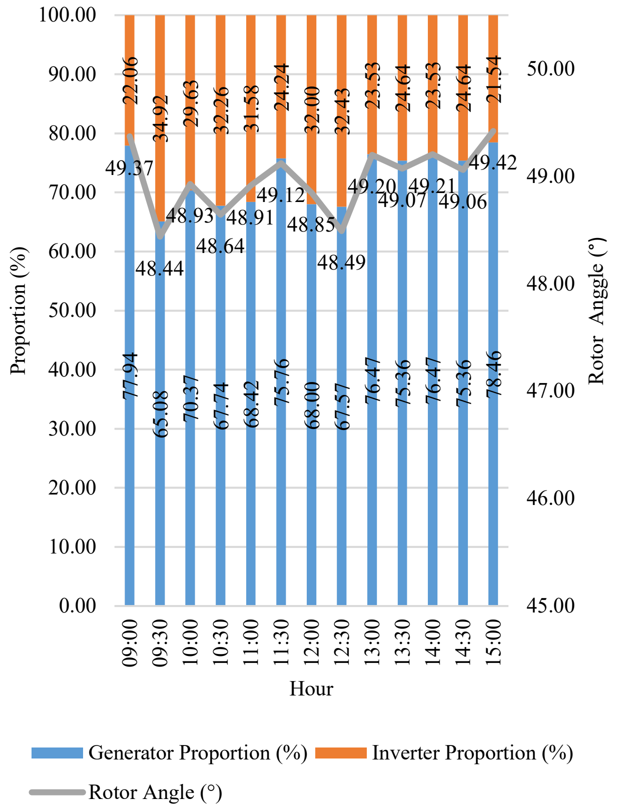

Figure 6. Angle Calculation Analysis Diagram with R-Phase Proportion

The dataset outlined in Table V. comprehensively illustrates the performance of the hybrid power system by detailing the generator power output, inverter power output, their respective proportional contributions to the total power supply, as well as the corresponding rotor angle (∂) for Phase-R. These values are recorded consistently at 30-minute intervals, spanning from 09:00 to 15:00, thereby providing a clear temporal overview of system behavior throughout a typical operational period.

Throughout the observation period, generator power output remains consistently high, maintaining a dominant role in the energy supply profile. It demonstrates noticeable peaks during the morning and afternoon hours, underscoring its reliability as a primary power source. In contrast, inverter power output displays a greater degree of variability, responding dynamically to changes in solar irradiance as the day progresses.

The generator's share of the total power supply remains predominant across the entire time range. It begins at a high value of 77.94% at 09:00, slightly diminishes around midday when solar contribution is more significant, and then rises once again in the afternoon. This fluctuation suggests a strategic interplay between generator and inverter to balance power generation. Conversely, the inverter's proportional contribution reaches its highest point during midday hours, coinciding with the peak availability of solar energy, which is typical in photovoltaic-based systems.

The rotor angle (∂), which reflects system stability, remains relatively stable with minor fluctuations. It is higher in the morning and afternoon, when the generator's power contribution is substantial, with the rotor angle around 49°. As the inverter's contribution increases at midday, the rotor angle decreases slightly, indicating a balancing of power distribution. In the afternoon, as the generator's contribution increases again, the rotor angle stabilizes. Overall, the data indicates that the hybrid system maintains stable performance throughout the day.

TABLE VI. Results of Angular Calculation Analysis with S-Phase Proportion

Hour	Phase S				
	Generator Power (W)	Inverter Power (W)	Generat-or Proporti-on (%)	Inverter Propor-tion (%)	Rotor Angle (°)
09:00	101,43	34,64	74,55	25,45	49,39
09:30	110,81	66,49	62,50	37,50	44,11
10:00	111,58	55,79	66,67	33,33	47,02
10:30	117,00	68,25	63,16	36,84	45,05
11:00	103,84	77,88	57,14	42,86	41,26
11:30	128,37	45,31	73,91	26,09	48,91
12:00	128,75	60,59	68,00	32,00	48,83
12:30	122,78	71,62	63,16	36,84	44,34
13:00	106,97	66,22	61,76	38,24	42,49
13:30	108,58	63,13	63,24	36,76	45,34
14:00	124,80	61,18	67,11	32,89	48,01
14:30	125,23	60,11	67,57	32,43	48,50
15:00	125,42	33,77	78,79	21,21	50,62

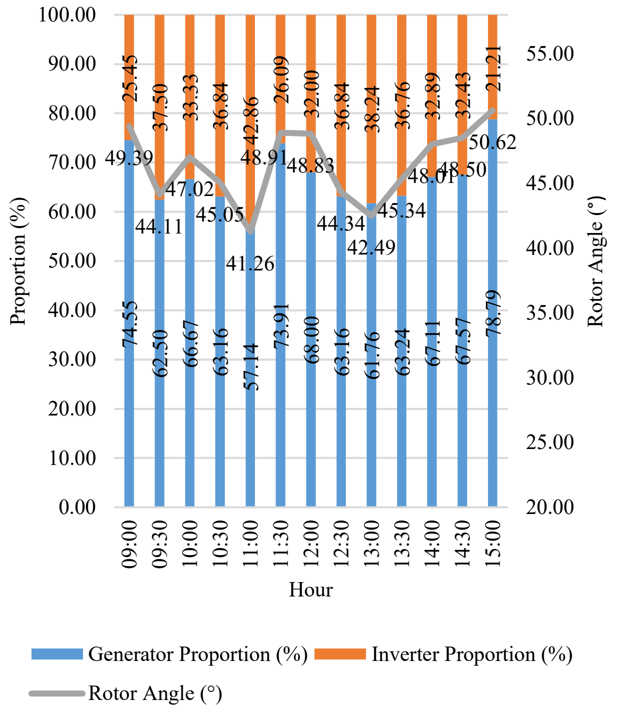

Figure 7. Angle Calculation Analysis Diagram with S-Phase Proportion

Table VI. presents data for Phase-S on generator power, inverter power, their proportions, and the rotor angle at 30-minute intervals from 09:00 to 15:00: at 09:00, the generator power is 101.43 W with a proportion of 74.55%, while the inverter power is 34.64 W at 25.45%, and the rotor angle is 49.39°; by 11:00, generator power decreases to 103.84 W with a proportion of 57.14%, inverter power increases to 77.88 W at 42.86%, and the rotor angle drops to 41.26°; by 15:00, generator power rises to 125.42 W with the highest proportion of 78.79%, inverter power decreases to 33.77 W at 21.21%, and the rotor angle increases to 50.62°.

TABLE VII. RESULTS OF ANGULAR CALCULATION ANALYSIS WITH T-PHASE PROPORTION

Hour	Phase T				
	Generator Power (W)	Inverter Power (W)	Generator Proportion (%)	Inverter Proportion (%)	Rotor Angle (°)
09:00	123,70	38,81	76,12	23,88	49,06
09:30	120,64	39,39	75,38	24,62	48,59
10:00	108,66	42,96	71,67	28,33	43,57
10:30	127,68	47,57	72,86	27,14	47,37
11:00	106,97	58,58	64,62	35,38	42,60
11:30	121,74	42,24	74,24	25,76	47,62
12:00	129,08	63,28	67,11	32,89	43,19
12:30	122,70	47,58	72,06	27,94	44,04
13:00	98,83	50,68	66,10	33,90	42,75
13:30	101,36	64,98	60,94	39,06	41,84
14:00	104,84	63,93	62,12	37,88	42,46
14:30	101,66	34,71	74,55	25,45	47,96
15:00	98,04	31,86	75,47	24,53	48,76

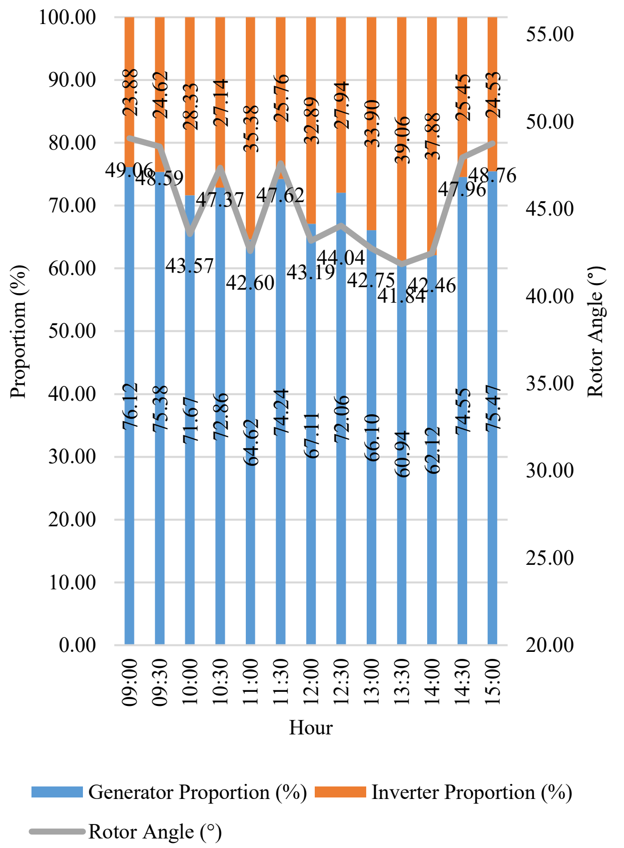

Figure 8. Angle Calculation Analysis Diagram with T-Phase Proportion

Table VII. presents data for Phase-T on generator power, inverter power, their respective proportions, and rotor angle at 30-minute intervals from 09:00 to 15:00: at 09:00, the generator power is 123.70 W with a proportion of 76.12%, while the inverter power is 38.81 W at 23.88%, and the rotor angle is 49.06°; by 11:00, generator power decreases to 106.97 W with a proportion of 64.62%, inverter power increases to 58.58 W at 35.38%, and the rotor angle drops to 42.60°; by 15:00, generator power is 98.04 W with a proportion of 75.47%, inverter power decreases to 31.86 W at 24.53%, and the rotor angle is 48.76°. The analysis of angular calculation across the three phases (R, S, and T) reveals that the generator consistently contributes more power to the system, particularly in the morning and afternoon, while the inverter's contribution peaks around midday, aligning with peak solar energy availability. Despite minor fluctuations, the rotor angle remains stable across all phases, indicating effective system stability. However, the data also suggest that as the inverter's contribution increases, especially around midday, the rotor angle tends to decrease, highlighting a potential synchronization challenge as photovoltaic supply grows. This underscores the need to balance generator and inverter contributions to maintain synchronization, and further investigation could focus on optimizing system performance and evaluating the impact of environmental conditions on stability and efficiency.

IV. CONCLUSION

This hybrid energy system demonstrates stable and effective performance in managing power distribution throughout the day. The generator acts as the primary contributor to maintaining stability in the morning and afternoon, while the inverter significantly contributes during peak solar hours at midday. The rotor angle and the power supply proportions of the generator and inverter are interconnected; as the generator's supply proportion decreases and the inverter's proportion increases, the rotor angle shifts to a smaller value, and vice versa. Despite these shifts, the rotor angle tends to remain stable with minor fluctuations, highlighting the system's ability to adapt to changing power contributions from the generator and inverter. These findings confirm that the combination of generators and inverters in a hybrid system can efficiently support the stability and efficiency of power distribution. Further research could explore the effects of incorporating additional renewable energy sources, such as wind power, into the system. Additionally, long-term stability analysis under varying load conditions would provide valuable insights for optimizing system performance.

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