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Active and Reactive Power Distribution in the Parallel Operation of Synchronous Generators in A Medium-Voltage System at PT. PLTMGU Peaker Lombok

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ABSTRACT: This study analyzes the performance of a multi-generator power system operating in parallel, focusing on active power, reactive power, power factor, and load sharing. Data collected over three days were evaluated using statistical methods and three-phase power analysis. Results indicate that total active power remained stable on the first and second days (94.41 MW and 93.69 MW) but decreased to 63.39 MW on the third day due to fewer operating generators. Reactive power shifted from capacitive (-11.36 MVAr) on the first day to inductive conditions on the second and third days (15.55 MVAr and 14.16 MVAr). The power factor improved from 0.99 leading to approximately 0.98 lagging, indicating more optimal operation. Load sharing analysis shows the third day had the most balanced distribution (σ ≈ 90 kW), compared to the first (σ ≈ 480 kW) and second days (σ ≈ 740 kW). Voltage and frequency remained stable within 14.93–15.13 kV and 49.99–50.13 Hz. These findings highlight the importance of reactive power control and coordinated load sharing to enhance system efficiency and stability.

KEYWORDS: Multi-generator system; Active power distribution; Reactive power control; Power factor; Load sharing balances

I. INTRODUCTION

1.1 Background

The increasing demand for electrical energy requires power generation systems to operate in a more reliable, flexible, and efficient manner[1]. One of the commonly applied approaches in modern power systems is the parallel operation of multiple generators within a single power network[2]. This configuration enables the system to adjust power capacity according to varying load demands[3], thereby improving system stability and ensuring continuity of power supply[4]. In addition, multi-generator configurations enhance system reliability, as the failure of one unit can be compensated by other operating units[5][6]. In multi-generator power systems, load sharing among generators becomes a critical aspect[7]. Each generator must share the load proportionally according to its capacity and operational characteristics[8]. This process involves both active and reactive power distribution, which must be properly controlled to avoid system imbalance[9]. Uneven load distribution may lead to overloading of certain generators, reducing operational efficiency and accelerating equipment degradation[10][11]. Reactive power management also plays a vital role in maintaining voltage stability within the power system. Improper reactive power control can result in voltage imbalance and fluctuations, ultimately degrading power quality delivered to consumers[12]. Furthermore, reactive power imbalance can negatively impact generator stability, increase power losses, and reduce overall system performance[13] [14]. Based on these issues, this study aims to analyze the distribution of active and reactive power in a multi-generator parallel system using operational parameters such as active power, reactive power, power factor, voltage, and current. The results are expected to provide insights into load sharing conditions and overall system performance, contributing to improved efficiency and stability of multi-generator power systems.

1.2 Literature Review (State of the Art)

Several previous studies have extensively discussed the parallel operation of synchronous generators, particularly in relation to load sharing, reactive power control, and power system stability[15]. Parallel operation is widely applied in modern power systems to enhance reliability and operational flexibility[16]. In such systems, proportional power sharing among generators is essential to maintain stable and efficient operation. Classical studies, such as those by Wang et al. (1994), indicate that the balance between active and reactive power is a key factor in maintaining system stability[17]. Imbalanced power distribution may lead to voltage fluctuations, frequency instability, and potential disturbances in power generation systems. Moreover, other studies have shown that proper power factor control and reactive power management significantly improve system efficiency[18]. Effective reactive power control not only stabilizes voltage but also reduces power losses in transmission and distribution networks[19]. Therefore, optimal management of both active and reactive power is essential to maintain system performance and ensure high-quality power delivery.

1.3 Research Gap

Most existing studies on parallel operation of synchronous generators focus on control strategies and simulation-based analyses to improve the accuracy of active and reactive power sharing. Various methods, such as droop control[20], virtual impedance control, and virtual synchronous generator strategies, have been developed to enhance system stability and ensure proportional load sharing[21].

Although these approaches provide valuable theoretical insights, they are generally based on idealized system models or controlled microgrid scenarios. Consequently, they do not fully represent real-world operating conditions of multi-generator systems[22][23].

Therefore, studies based on actual operational data of parallel generators remain limited, particularly in evaluating active and reactive power distribution and load sharing under real conditions[24]. This gap highlights the need for research based on real operational data to provide a more representative understanding of multi-generator system performance in practical applications.

II. METHODOLOGY

The research methodology is designed to analyse the performance of a power generation system consisting of multiple synchronous generators operating in parallel. The approach used is based on actual operational data analysis by utilizing key power system parameters, namely active power (P), reactive power (Q), power factor (cosφ), voltage (V), and current (I). The analysis is carried out systematically to obtain a comprehensive understanding of load distribution and operating conditions of the power generation system.

The first step is to identify the generators that are actively operating in the system. This identification is based on the active power data of each generator, where generators with active power greater than zero ($P_i > 0$) are categorized as active. Mathematically, this condition is expressed as:

$$P_i > 0 \tag{1}$$

Generators with ($P_i = 0$) are considered inactive and excluded from further analysis.

The second step involves calculating the total active power of the system, which represents the sum of power contributions from all active generators:

$$P_{total} = \sum_{i=1}^{n} P_i \tag{2}$$

where (n) is the number of active generators. The next step is calculating the total reactive power:

$$Q_{total} = \sum_{i=1}^{n} Q_i \tag{3}$$

This parameter plays a crucial role in maintaining system voltage stability. Subsequently, the system power factor is analyzed. The apparent power (S) is calculated as:

$$S = \sqrt{P_{total}^2 + Q_{total}^2} \tag{4}$$

and the power factor is expressed as:

$$\cos\phi = \frac{P_{total}}{S} \tag{5}$$

A power factor close to unity indicates efficient operation with minimal power losses. For each generator, the three-phase power equations are used for verification:

$$P = \sqrt{3}\,VI\cos\phi \tag{6}$$

$$Q = \sqrt{3}\,VI\sin\phi \tag{7}$$

Finally, load sharing balance among generators is evaluated by calculating the average active power:

$$P_{avg} = \frac{P_{total}}{n} \tag{8}$$

and the deviation:

$$\Delta P_i = |P_i - P_{avg}| \tag{9}$$

Smaller deviation values indicate better load sharing balance, while large deviations may suggest issues in control systems such as governor settings or Automatic Voltage Regulator (AVR). Overall, this methodology provides a comprehensive analysis of multi-generator system performance, particularly in terms of active and reactive power distribution, system efficiency, and load sharing balance, based on real operational data.

III.RESULTS AND DISCUSSION

This study utilizes three sets of generator operational data representing different operating conditions, namely the initial condition, the second-day condition, and the third-day condition, as well as illustrating system conditions with capacitive reactive power characteristics. Figure 1(a) shows the total number of generating units installed at the site, while Figure 1(b) presents the monitoring system used to ensure the accuracy of the data displayed in the system.

(a)

(b)

Figure 1. Power Plant Location: (a) Total generating units at the site; (b) Monitoring and display system

Table 1 presents the main engine specifications of the PLTMGU system used in this study. The engine is of type W20V34DF with a 20-cylinder configuration, a cylinder bore of 340 mm, and a piston stroke of 400 mm, designed to achieve optimal performance at an operating speed of 750 rpm. The engine has a rated output of 10,000 kW, supporting medium- to large-scale power generation requirements. The main electrical system operates at a voltage of 400 V with a frequency of 50 Hz and is equipped with a secondary voltage system of 24 VDC. The engine utilizes a wet sump lubrication system and operates with a clockwise rotation direction.

Table 1 Specification e*ngine* for PLTMGU

`Spesification	Type
Engine Type	W20V34DF
Number of Cylinders	20
Cylinder Bore	340 mm
Stroke	400 mm
Speed	750 rpm
Rated Output	10.000kW
Main Voltage	400 V; 50 Hz
Secondary Voltage	24 VDC
Oil Sump Type	Wet
Rotation direction	Clockwise

Table 2 presents the generator operational data on the first day, reflecting the power generation system under high load conditions with predominantly capacitive reactive power characteristics. Out of the 13 installed generators, 11 units were actively operating, namely G1, G2, G3, G4, G6, G8, G9, G10, G11, G12, and G13, while G5 and G7 were not in operation.

Table 2 First-day data

Gen	Actif power	Reactif power	Cos Φ	Freq	Voltag (3 fase)
G1	8477	-1050	-0,99	50,04	15,04
G2	8506	-960	-0,99	50,04	15,04
G3	8543	-932	-0,99	50,04	15,04
G4	9535	-1121	-0,99	50,04	15,04
G5	0	0	1,0	0	0
G6	9492	-1240	-0,99	50,05	15,04
G7	0	0	1,0	0	0
G8	8492	-1012	-0,99	49,99	14,93
G9	8544	-1119	-0,99	49,99	14,93
G10	8518	-957	-0,99	49,99	14,93
G11	8275	-1049	-0,99	49,99	14,93
G12	8112	-998	-0,99	49,99	14,93
G13	7912	-925	-0,99	49,99	14,93

The active power ranged from 7,912 kW to 9,535 kW, with the highest output recorded at G4 (9,535 kW) and G6 (9,492 kW), and the lowest at G13 (7,912 kW). All active generators exhibited negative reactive power values, ranging from -925 kVAr to -1,240 kVAr, indicating that the system operated under capacitive conditions with a power factor of approximately -0.99 (leading). This condition may lead to voltage imbalance if not properly controlled. The system voltage remained within 14.93–15.04 kV, while the frequency was relatively stable in the range of 49.99–50.05 Hz, indicating synchronous operation. However, the variation in active power among generators remains significant, suggesting that load sharing is not yet optimal and requires adjustments in control systems such as governor settings or excitation control.

Table 3 presents the generator operational data on the second day, reflecting the power generation system under inductive reactive power characteristics, which are closer to normal operating conditions. Out of a total of 13 generator units, 11 generators were actively operating, namely G1, G2, G3, G4, G7, G8, G9, G10, G11, G12, and G13, while G5 and G6 were not in operation. The active power ranged from 7,496 kW to 9,441 kW, with the highest values recorded at G4 (9,441 kW) and G7 (9,429 kW), while the lowest value was observed at G10 (7,496 kW). Unlike the first day, all active generators exhibited positive reactive power values, ranging from 641 kVAr to 1,871 kVAr, indicating that the system operated under inductive conditions with a power factor between 0.98 and 1.00 (lagging). This condition reflects an improvement in reactive power management, which plays a crucial role in maintaining system voltage stability. The system voltage remained relatively stable within the range of 14.96–14.97 kV, while the frequency was constant at 50.13 Hz. However, the variation in active power among generators is still significant, indicating that load distribution has not yet been fully balanced and requires further optimization in governor and excitation control systems.

.Tabel 3 Second-day data

Gen	Actif power	Reactif power	Cos Φ	Frequency	Voltage (3 fase))
G1	8524	1871	0,98	50,13	14,97
G2	8523	1481	0,99	50,13	14,97

G3	8549	1519	0,98	50,13	14,97
G4	9441	1587	0,99	50,13	14,97
G5	0	0	1,0	0	0
G6	0	0	1,0	0	0
G7	9429	1292	0,99	50,13	14,97
G8	7516	1253	0,99	50,13	14,96
G9	7562	1193	0,99	50,13	14,96
G10	7496	641	1,0	50,13	14,96
G11	7560	1198	0,99	50,13	14,96
G12	7529	1239	0,99	50,13	14,96
G13	7562	1271	0,99	50,13	14,96

Table 4 presents the generator operational data on the third day, reflecting a more stable and balanced power generation system compared to the previous days. Out of the 13 available generator units, 8 generators were actively operating, namely G1, G3, G4, G7, G9, G10, G11, and G12, while G2, G5, G6, G8, and G13 were not in operation. The active power ranged within a relatively narrow band, from 7,827 kW to 8,037 kW, with the highest value recorded at G11 (8,037 kW) and the lowest at G1 (7,827 kW). This narrow range indicates that load distribution among generators was well balanced.

Tabel 4 third-day data

Gen	Actif power	Reactif power	Cos Φ	Freq	Voltage (3 fase))
G1	7827	1712	0,98	50,05	15,11
G2	0	0	1,0	0	0
G3	7832	1856	0,97	50,05	15,11
G4	7840	1774	0,98	50,05	15,11
G5	0	0	1,0	0	0
G6	0	0	1,0	0	0
G7	7837	1747	0,98	50,05	15,11
G8	0	0	1,0	0	0
G9	8025	1721	0,98	50,04	15,13
G10	7979	1820	0,97	50,04	15,13
G11	8037	1751	0,98	50,04	15,13
G12	8012	1781	0,98	50,04	15,13
G13	0	0	1,0	0	0

All active generators exhibited positive reactive power values, ranging from 1,712 kVAr to 1,856 kVAr, indicating that the system operated under inductive conditions with a power factor between 0.97 and 0.98. The system voltage remained within the range of 15.11–15.13 kV, and the frequency was relatively stable at 50.04–50.05 Hz, demonstrating stable system operation. Overall, the relatively small variation in both active and reactive power indicates that the system achieved optimal load sharing performance and more efficient and controlled operating conditions on the third day

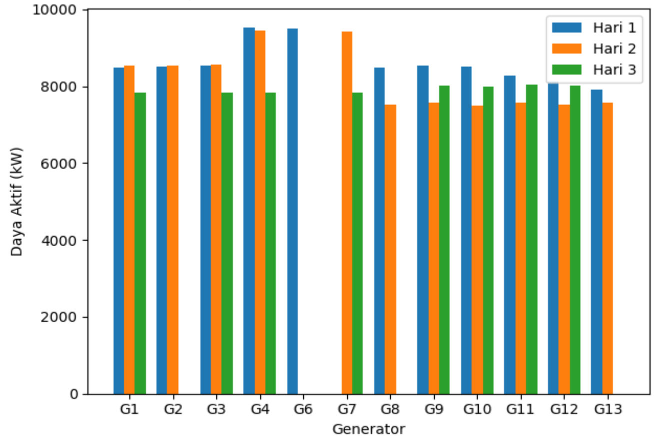

Figure 2. Comparison of Generator Active Power Over Three Days

Figure 2 presents a comparison of generator active power over three days of operation, showing significant variations in load distribution. On the first day, the active power ranged from approximately 7,912 kW to 9,535 kW, with the highest value recorded at G4 (9,535 kW) and G6 (9,492 kW), while the lowest value was observed at G13 (7,912 kW). On the second day, the active power ranged between 7,496 kW and 9,441 kW, where G4 and G7 generated 9,441 kW and 9,429 kW, respectively, while G10 recorded the lowest value at 7,496 kW. On the third day, the active power distribution became more uniform, with a narrower range between 7,827 kW and 8,037 kW. The highest value was recorded at G11 (8,037 kW), while the lowest was at G1 (7,827 kW). This indicates that the variation in active power on the third day is significantly smaller compared to the previous days, reflecting more optimal and stable load sharing conditions.

Table 5. System Performance

Parameter	Day 1	Day 2	Day 3
Total (P)	94.41 MW	93.69 MW	63.39 MW
Total (Q)	-11.36 MVAr	+15.55 MVAr	+14.16 MVAr
Power Factor (PF)	0.99 leading	0.98 lagging	0.98 lagging
Load Sharing	Uneven	Less balanced	Very good
Conditions	Capacitive	Inductive	Inductive

Table 5 shows that the active power remains relatively stable on the first and second days, and then decreases on the third day. A transition in reactive power characteristics occurs from capacitive to inductive. The power factor improves toward a lagging condition, while load sharing increases and reaches the most optimal condition on the third day.

Table 6. Active Power Statistics of Generators

Gen	Mean P (kW)	Min P (kW)	Max P (kW)	Operating Status
G1	8276	7827	8524	Stable
G2	8506	8506	8506	Fluctuating (off for 2 days)
G3	8308	7832	8549	Stable
G4	8939	7840	9535	High load
G5	0	0	0	Inactive
G6	9492	9492	9492	Fluctuating (off for 2 days)
G7	8633	7837	9429	Fluctuating
G8	8004	7516	8492	Fluctuating
G9	8044	7562	8544	Stable
G10	7998	7496	8518	Stable
G11	7957	7560	8275	Stable
G12	7884	7529	8112	Stable
G13	7737	7562	7912	Stable

Table 6 presents the active power statistics of generators over three days of operation, reflecting the performance characteristics of each unit. Most generators, such as G1, G3, G9, G10, G11, G12, and G13, exhibit stable operation with average active power values ranging from 7,737 kW to 8,308 kW. Generators G4 and G6 show higher power levels, with G4 reaching a maximum of 9,535 kW and G6 remaining constant at 9,492 kW, indicating high loading conditions. Meanwhile, several generators, including G2, G7, and G8, display fluctuating operational patterns. Generator G5 was not in operation during the observation period. Overall, these data indicate variations in load distribution among the generators.

Table 7 presents the reactive power statistics of the generators, illustrating diverse operational characteristics during the observation period. Most generators exhibit variable patterns, indicated by a range from negative minimum values to positive maximum values, as observed in G1, G3, and G10. This reflects transitions in system conditions from capacitive to inductive behavior. Generator G7 demonstrates a consistently inductive characteristic with the highest average value of 1520 kVAr, whereas G6 exhibits a capacitive nature with a constant value of -1240 kVAr. Generator G5 was not in operation during the observation period.

Table 7. Reactive Power Statistics of Generators

Generator	Mean Q (kVAr)	Min Q (kVAr)	Max Q (kVAr)	Characteristics
G1	844	-1050	1871	Variable
G2	260	-960	1481	Variable
G3	814	-932	1856	Variable
G4	747	-1121	1774	Variable
G5	0	0	0	Inactive
G6	-1240	-1240	-1240	Capacitive
G7	1520	1292	1747	Inductive
G8	121	-1012	1253	Variable
G9	598	-1119	1721	Variable
G10	501	-957	1820	Variable
G11	633	-1049	1751	Variable
G12	674	-998	1781	Variable
G13	173	-925	1271	Variable

Overall, the variation in reactive power indicates dynamic excitation control and changing system conditions.

Table 8 shows the power factor statistics of the generators, describing the operational characteristics of the power system during the observation period. Most generators have average power factor values in the range of 0.32–0.33, with a very wide range between minimum and maximum values, from -0.99 to 0.99. This range indicates that the system experiences transitions between capacitive (leading) and inductive (lagging) operating conditions, reflecting fluctuations in reactive power management. Generator G6 consistently operates under capacitive conditions with a power factor of -0.99, indicating the dominance of negative reactive power. Meanwhile, G5 remains inactive with a constant value of 1.00. Generator G7 has a higher average value of 0.66, indicating a more inductive operating tendency. Overall, this variation in power factor suggests that the system has not yet reached an optimal stability condition in reactive power regulation.

Table 9 indicates a significant improvement in load distribution from the first day to the third day. On the second day, the active power deviation reached its highest value ($\sigma \approx$ 740 kW), indicating an uneven load sharing among the generators.

Table 8. Power Factor Statistics

Gen	Mean cosφ	Min	Max	Characteristic
G1	0.32	-0.99	0.98	Variable
G2	0.33	-0.99	0.99	Variable
G3	0.32	-0.99	0.98	Variable
G4	0.33	-0.99	0.99	Variable
G5	1.00	1.00	1.00	Off
G6	-0.99	-0.99	-0.99	Capacitive
G7	0.66	-0.99	0.99	Variable
G8	0.00	-0.99	0.99	Variable

Gen	Mean cosφ	Min	Max	Characteristic
G9	0.32	-0.99	0.99	Variable
G10	0.32	-0.99	1.00	Variable
G11	0.32	-0.99	0.99	Variable
G12	0.32	-0.99	0.99	Variable
G13	0.33	-0.99	0.99	Variable

Table 9. Standard Deviation Comparison

Parameter	Day 1	Day 2	Day 3
σ P (kW)	480	740	90
σ Q (kVAr)	95	320	50
Load Sharing	Uneven	Very Poor	Very Good
VAR System	Capacitive	Inductive (Unstable)	Inductive (Stable)

In contrast, on the third day, the deviation decreased significantly (σ ≈ 90 kW), reflecting a more balanced system condition. A similar trend is observed in reactive power, where the largest deviation also occurs on the second day, indicating instability in reactive power distribution. These results confirm that the operating condition on the third day represents the most stable and optimal condition compared to the other days.

IV. CONCLUSION

Based on the analysis of generator operational data over three days, the power generation system exhibits dynamic characteristics, particularly in reactive power distribution and load balancing. On the first day, the system operates under capacitive conditions with reactive power of -11.36 MVAr and a power factor of approximately 0.99 (leading), indicating reactive power overcompensation. On the second and third days, the system shifts to inductive conditions with reactive power values of 15.55 MVAr and 14.16 MVAr, respectively, and a power factor of approximately 0.98 (lagging), which is closer to the ideal operating condition. The active power remains relatively stable in the range of 93.69–94.41 MW during the first and second days but decreases to 63.39 MW on the third day due to a reduction in the number of active generators. The standard deviation analysis shows that the third day has the most evenly distributed load (σ ≈ 90 kW), compared to the first day (σ ≈ 480 kW) and the second day (σ ≈ 740 kW), indicating optimal and stable load sharing conditions.

Optimization of the governor control and excitation system is required to stabilize reactive power distribution and maintain the power factor within the range of 0.95–0.98, ensuring efficient and stable system operation.

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