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Technical evaluation of kVar import anomalies on main transformer number 2 at Siman Hydroelectric

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ABSTRACT

An issue of reactive power import (negative kVar) was identified in Main Transformer No. 2 at PLTA Siman, resulting from mismatched voltage ratios and impedance values among parallel-operated transformers. This mismatch induced a circulating current and led to reactive power being absorbed from the external grid, increasing energy losses and operational costs. This study aims to investigate the root cause of the anomaly, propose technical solutions, and evaluate their effectiveness. The analysis was conducted out through system simulation using ETAP software, testing three technical scenarios: installation of a 569.9 kVar capacitor bank, implementation of a Standard Operating Procedure (SOP) for PMT disconnection during standby conditions, and replacement of the transformer with one that matches the specifications of the other units. The simulation results revealed that SOP implementation eliminated kVar import by 100% during standby, the capacitor bank reduced it by approximately 70%, and transformer replacement fully eliminated the circulating current. The findings suggest that a combined approach involving SOP and capacitor installation offers an optimal solution without major infrastructure replacement.

Keywords: kVar import; circulating current; capacitor bank; operational SOP; parallel transformers

1. Introduction

Transformers are vital components in electrical power systems, especially in parallel operation configurations that are widely used in power plants. When transformers with non-identical specifications are operated in parallel, power distribution imbalances and circulating currents can occur. One consequence of this condition is the occurrence of kVar import, which involves the absorption of reactive power from the external grid into the internal power plant system. This can potentially reduce operational efficiency and increase operational costs due to kVar charges imposed by the electricity supplier [1][2].

Previous studies have discussed efforts to control reactive power through the installation of capacitor banks and improving the power factor in distribution systems. Showed that the use of capacitor banks can significantly reduce reactive power consumption and improve power quality [3]. Investigated the effect of transformer impedance on circulating current in parallel systems and emphasized the importance of technical parameter compatibility between transformers to maintain power distribution stability [4]. Highlights the benefits of implementing standard operating procedures (SOPs) in improving system reliability, although this has not been specifically examined in the context of controlling kVar import [5].

However, these studies generally focus on conventional distribution systems and do not specifically highlight the parallel configuration of transformers in power generation units [6], such as hydroelectric power plants [7]. In addition, there have not been many studies that comprehensively examine the effectiveness of combining several technical approaches in reducing kVar import. This gap forms the basis for the originality of this research [8].

This study specifically examines the phenomenon of kVar import in Main Transformer No. 2 of the Siman Hydroelectric Power Plant, which is caused by a mismatch in voltage ratio and impedance between transformers operating in parallel [9]. Using a simulation-based approach with ETAP software, this article evaluates three technical solutions: installing a capacitor bank, implementing an SOP for PMT disconnection during standby conditions, and replacing the transformer [10]. The main contribution of this research is to provide simulation-based solutions for reactive power anomalies in hydroelectric power generation systems, which can be applied without requiring major interventions to the main equipment.

2. Method

The object of this study is the internal distribution system of the Siman Hydroelectric Power Plant located in East Java, Indonesia. This power plant has a total generation capacity of 3 × 3.5 MW and uses three main transformers (Main Trafo) with a capacity of 6 MVA each, configured in a parallel bus transformer system [11]. The primary focus of the research is on Main Trafo No. 2, which exhibits anomalous symptoms in the form of reactive power import (kVar import). All three transformers are modeled in the simulation based on actual parameters from field conditions [12].

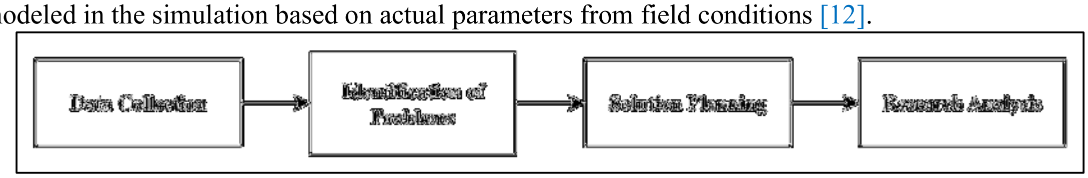

Figure 1**.** Research flow

Data Collection

Table 1, according to the Kvar meter history data stored in the Kvar meter data logger, the abnormal kVar import anomaly began with the replacement of Main Transformer No. 2 at the Siman Hydroelectric Power Plant, with specifications for the HV & LV voltage ratio that were not the same as the existing main transformer. The Kvar recording began to indicate the presence of circulating current, which caused reverse current in the recording device, which was then read as Kvar import. The emergence of circulating current is a result of differences in impedance values that affect the direction of current flow in part and cause circulating current in the transformer windings, thereby influencing the Kvar calculation in the Kvar meter recording device [13].

Table 1. Total kWh and kVarh Import Records for Siman Hydroelectric Power Plant

Unit	Total kWh dan kVarh 2019		
	kWh Impor	kVar Standby	Total Bill (Rp)
Siman I	2.501,00	812,00	7.074.585,66
Siman II	6.897,00	70.651,00	41.949.035,64
Siman III	2.698,00	715,00	7.452.411,54

Based on the data in Figure 2, which is drawn from the transaction records of the Siman Hydroelectric Power Plant from 2014 to February 2019, it can be seen that there is an anomaly in the import of kVarh that is outside normal usage, where MTR no. 2 experiences a different import of kVar compared to the normal conditions of units 1 & 3, where the generator should be sending Var (reactive power) to the transmission [14]. From the graph, it is also evident that circulating current affects the active power transmission process of Main Transformer No. 2, which is unbalanced (lower) compared to the energy production recorded in Main Transformers No. 1 and No. 3. There is a trend of increasing kVar imports from 2014 to 2023 and a trend of decreasing active power, posing a risk of active and reactive power being nearly equal, indicating that power losses will increase if Main Transformer No. 2 at PLTA Siman continues to operate [15]. Transformer No. 2 of the Siman Hydroelectric Power Plant absorbs VAR load, so the longer it is operated, the greater the percentage of apparent power margin (VAR) due to degradation of the core/winding material (impedance) of the Main Transformer itself, as indicated by anomalies in the test DGA.

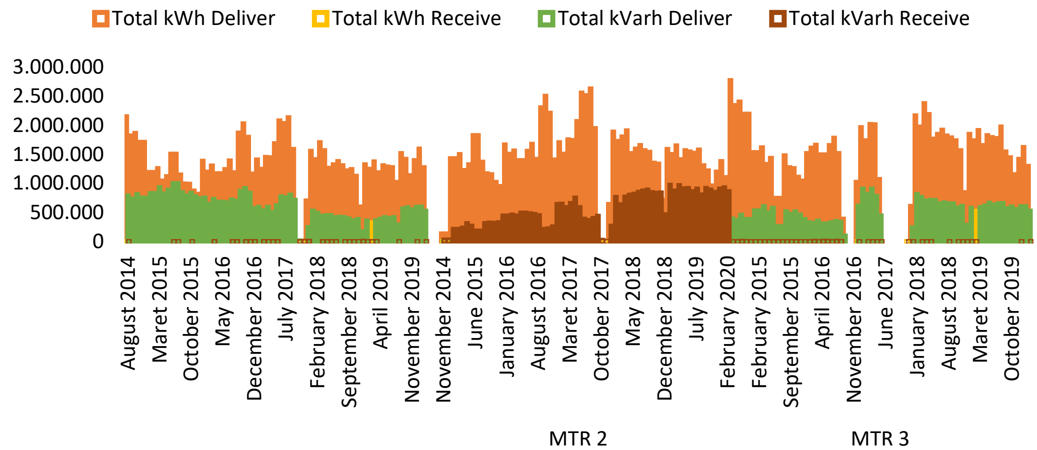

Figure 2. Siman hydroelectric power plant energy transaction chart

As shown in Table 2, the main transformers at the Siman Hydroelectric Power Plant consist of three units with similar technical specifications, but there are differences in voltage ratio and impedance, which are the focus of this study. Each transformer unit has a nominal capacity of 6 MVA and operates at a primary voltage of 70 kV and a secondary voltage of 6.3 kV, except for Main Trafo No. 2, which shows a slight deviation in voltage ratio compared to the other two transformers. Additionally, the impedance value of Main Transformer No. 2 is also different, which could potentially cause an imbalance in power distribution and circulating current between transformers when operated in parallel.

This difference in voltage and impedance ratios is believed to be the main cause of the kVar import phenomenon in Main Transformer No. 2. This mismatch affects the distribution of reactive load among the three transformers, whereby the other two transformers (No. 1 and No. 3) supply reactive power to the system normally, while Transformer No. 2 absorbs reactive power from the network. This technical specification information forms the basis for system modeling and simulation using ETAP software to analyze the impact of the proposed technical solutions [16].

Table 2. Specifications of Siman hydroelectric power plant main transformer

Spesifikasi	MTR 1		MTR 2		MTR 3	
Transformer number/ Serial number	PX-084-agca/19E000232		-/20262		-/PX16-0008	
Year of Manufacture	2019		2012		2016	
Year of Manufacture	2019		2012		2016	
Standard	IEC 60076		-		IEC 60076	
Rated Power	6 MVA		6 MVA		6 MVA	
Cooling	ONAN		ONAN		ONAN	
Frequency	50 HZ		50 HZ		50 HZ	
Phases	3		3		3	
Connection Symbol	YNd5		YnD5		YNd5	
Type of Oil	Nynas Nytro Libra		Shell Diala S2 ZU-I		Nynas Nytro Libra	
Tap Changer	HV	LV	HV	LV	HV	LV
1	77000	6000	73500	6450	77000	6000

Spesifikasi	MTR 1		MTR 2		MTR 3	
2	73500		71750		73500	
3	70000		70000		70000	
4	66500		68250		66500	
5	63000		66500		63000	
Ratio	11,66666667	1	11,39534884	1	11,66666667	1
	11,08333333		11,12403101		11,08333333	
			10,85271318			

Identification of problems

A discrepancy was found in the specifications of the Siman No. 2 hydroelectric power plant's main transformer compared to the other main transformers, specifically in the HV and LV voltage ratios. The main transformers for units #1 and #3 have HV ratings of 70,000 and LV ratings of 6,000, while the main transformer for unit #2 has HV ratings of 73,500 and LV ratings of 6,450. With the available tap changer options, it is not possible to achieve the same voltage ratio between the Main Transformer unit 2 and the Main Transformers #1 and #3. At the Siman Hydroelectric Power Plant, the existing Main Transformers function as a transformer bus system, so the voltage ratios between paralleled Main Transformers must be identical. If transformers connected in parallel have slightly different voltage ratios, due to the difference in induced EMF in the secondary windings, circulating current will flow in the loop formed by the secondary windings under no-load conditions, which may be significantly higher than the normal no-load current [17]. The current will be very high due to the low leakage impedance.

As shown in Figure 3, when two transformers with different voltage ratios are connected in parallel with the same primary supply voltage, there will be a difference in secondary voltage, and when the secondaries of these transformers are connected to the same bus, there will be circulating current between the secondaries and between the primaries as well. Since the internal impedance of the transformer is small, a small voltage difference can cause a sufficiently high circulating current. The primary and secondary ratings must be identical, or in other words, the transformers must have the same turn ratio, i.e., the same transformation ratio.

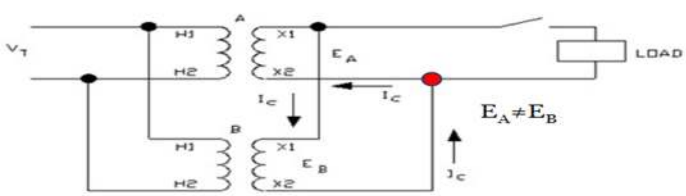

Figure 3. Parallel transformer operation

The explanation in Figure 4, it can be seen that the circulating current causes capacity loss when the main transformer operates as a voltage converter. When there is a difference in voltage ratio, current circulates between the transformer windings without any connected load, thereby reducing the power capacity of the transformer itself.

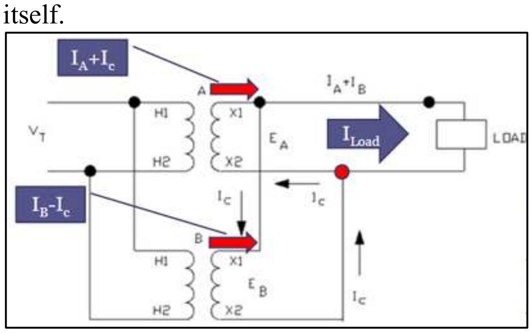

Figure 4. The impact of circulating currents

Figure 5 shows the existing SLD PLTA Siman simulation with ETAP, displaying the internal distribution system configuration of PLTA Siman in its actual condition, which has been modeled in ETAP. This figure shows three main transformers configured in a parallel bus transformer system to distribute power from three generating units to the distribution network.

Each transformer is displayed with voltage parameters, active power (kW), and reactive power (kVar) flowing in or out. The simulation results show that Main Transformer No. 1 and No. 3 are operating under normal conditions, where the reactive power displayed has a positive value (indicating reactive power output or export to the grid). Conversely, Main Transformer No. 2 shows a negative kVar value of –1342.9 kVar, indicating reactive power input (kVar import) to the transformer, not supplied to the system.

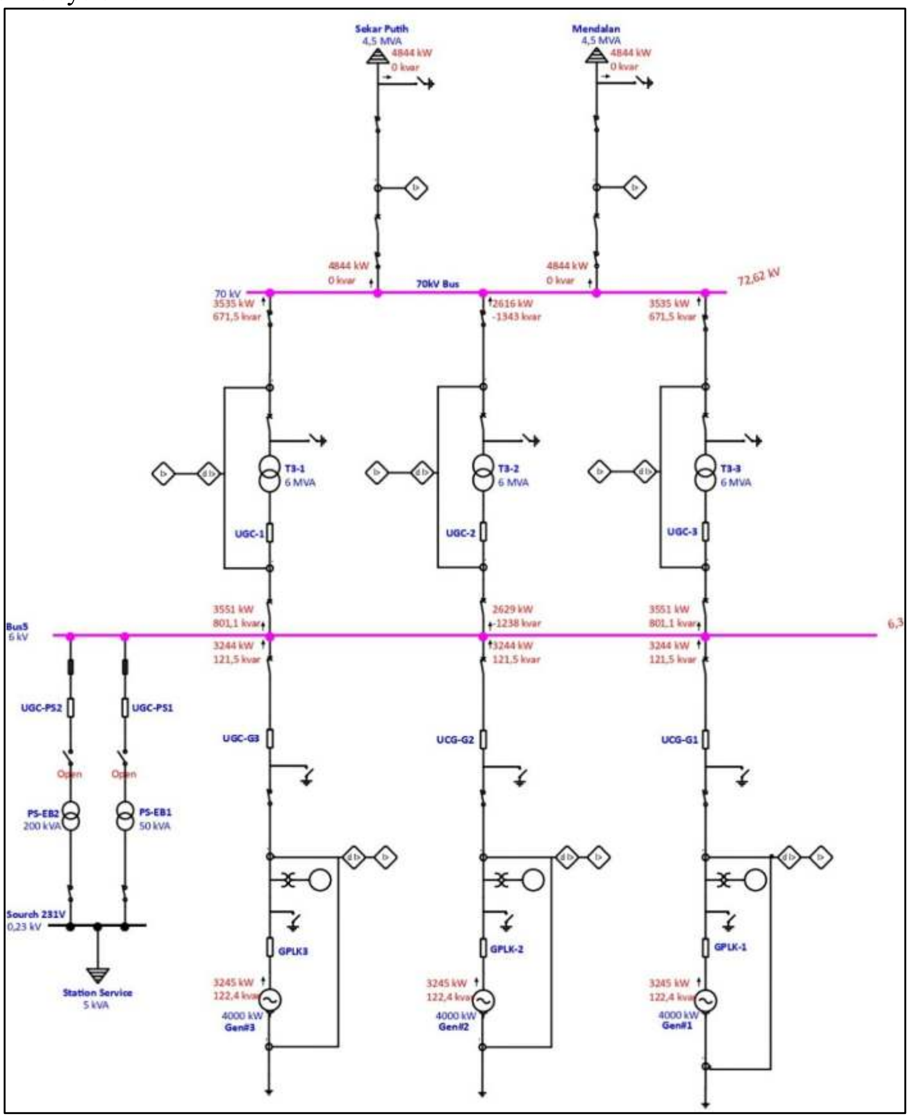

Figure 5. Simulation of existing conditions at Siman Hydroelectric Power Plant using ETAP

Based on the modeling of the existing system circuit shown in Figure 5 and Table 3 using ETAP software, a simulation was conducted by adjusting the real system parameters at the Siman Hydroelectric Power Plant. The simulation results indicate that Main Transformers No. 1 and No. 3 are operating normally, continuing to export reactive power (kVar). Meanwhile, Main Transformer No. 2 is experiencing an anomaly in the form of reactive power import (kVar) of 1342.9 kVar, indicating the absorption of reactive power from the power grid system [18].

Table 3. Simulation results of the Siman Hydroelectric Power Plant with ETAP

ID	Type	kW Flow	kvar Flow	Amp Flow	% PF	% Loading
T3-1	Transf. 2W	3550,7	800,6	333,8	97,55	60,7
ID	Type	kW Flow	kvar Flow	Amp Flow	% PF	% Loading
T3-2	Transf. 2W	2616,4	-1342,9	23,38	-88,97	49
T3-3	Transf. 2W	3550,7	800,6	333,8	97,55	60,7

Solution Planning

a) Application of capacitor banks

The application of a capacitor bank on the secondary side of Main Transformer No. 2 was implemented as a solution to compensate for the reactive power absorbed by the transformer due to anomalies in the voltage ratio. The calculation of the capacitor bank required by the system is as follows: The principle of operation of the capacitor bank is to supply capacitive reactive power as a form of compensation for the inductive reactive power required by the system [19][20]. The required capacitor capacity to improve the power factor can be calculated using the following equation:

$$Q_C = Q_1 - Q_2 \tag{1}$$

$$Q_2 = \sqrt{S^2 - P_2^2} \tag{2}$$

Transformer Capacity (S) = 6 MVA
Reaktive Power (Q_1) = 1342,9 kVar
Active Power (P) = 5847,8 kW
Capacitor Bank total (QC)= 569,9 kVar

Therefore, a 569.9 kVar capacitor bank will be installed on the 6 kV bus to provide local reactive power, thereby minimizing kVar imports from the network.

Addition of SOP related to the release of PMT Main Transformer No. 2 at Siman Hydroelectric Power Plant when the unit is on standby to avoid very high kVar Import.

SOP Objective:
- Preventing very high kVar imports when Main Transformer No. 2 is in standby mode.
- Reducing unnecessary reactive power so that it is not absorbed by the transformer.
- Reducing operational costs due to kVar import tariffs.

Conditions Requiring PMT Release:
- When the unit is not operating or in standby mode
- When Main Transformer No. 2 is not needed to support the power supply to the network (according to the results of data analysis No. 2).

SOP Steps [20].
- The operator monitors the status of the generator unit (unit is not in operation → standby status)
- Confirm that Main Transformer No. 2 is not being used to supply the load
- Coordinate between shifts/operators as well as with the maintenance team and transmission system controllers (UP2D or equivalent)
- Record the time, date, and system conditions at the time of disconnection in the operation log
- Perform the disconnection of Main Transformer No. 2 in accordance with safe switching procedures
- Use the standard checklist for switching procedures:
    a) PMT in open position
    b) Grounding applied (if any)
    c) Voltage indicator = zero
- Ensure there is no backfeed or residual voltage at the transformer terminals
- Monitor the system via SCADA to observe the effects of the disconnection on kVar parameters and system current
- Record changes in kVar values in the SCADA/kWh meter log
- Report in the daily report and weekly evaluation to the technical and management teams

Transformer replacement

In this scenario, Main Transformer No. 2 will be replaced with a new unit that has a primary and secondary voltage ratio that matches Main Transformers No. 1 and No. 3, thereby ensuring more stable and efficient parallel operation. In addition, the selection of the new transformer will take into account power capacity, impedance, and energy efficiency standards in order to improve the reliability of the power system at the Siman Hydroelectric Power Plant.

Table 4 Implementation and simulation of each solution

Table 4. Simulations were performed for each solution

Capacitor Bank Implementation	• Installing a 569.9 kVar capacitor bank on the secondary side of Main Transformer No. 2. • Simulations were conducted to calculate the decrease in imported kVar values and the increase in power factor after reactive power compensation.
Addition of PMT Release SOP	• The system was simulated with Main Transformer No. 2 disconnected when the unit was on standby. • An analysis was conducted on the system conditions before and after PMT release to observe its effect on reactive power flow.
Replacement of Main Transformer	• Replace Main Transformer No. 2 with a new unit that has the same voltage ratio as Main Transformers No. 1 and No. 3. • Simulations were conducted to evaluate the elimination of circulating current and kVar import.

3. Results and Discussion

This study was conducted to identify reactive power flow anomalies in the form of kVar imports in Main Transformer No. 2 of the Siman Hydroelectric Power Plant, which operates in a parallel transformer system (transformer bus). Based on historical data and simulation results using ETAP software, it was found that circulating currents between transformers occurred due to mismatches in voltage ratios and impedance, causing Transformer No. 2 to absorb reactive power from the grid instead of supplying it as intended. This is indicated by a negative reactive power value of -1,342.9 kVar, indicating reactive power import. To evaluate and address this issue, the study designed and compared three technical solution scenarios, namely:

Application of capacitor banks

In this scenario, a 569.9 kVar capacitor bank was added to the secondary side of Main Transformer No. 2. The aim was to provide local reactive power compensation, thereby reducing the amount of reactive power imported from the grid. Simulations show that this implementation can significantly reduce the imported kVar value to near zero, depending on the size of the capacitor and actual load conditions. These results confirm that reactive power compensation through a capacitor bank effectively reduces the system's reactive load. The simulation of the capacitor bank implementation is shown in Figure 6.

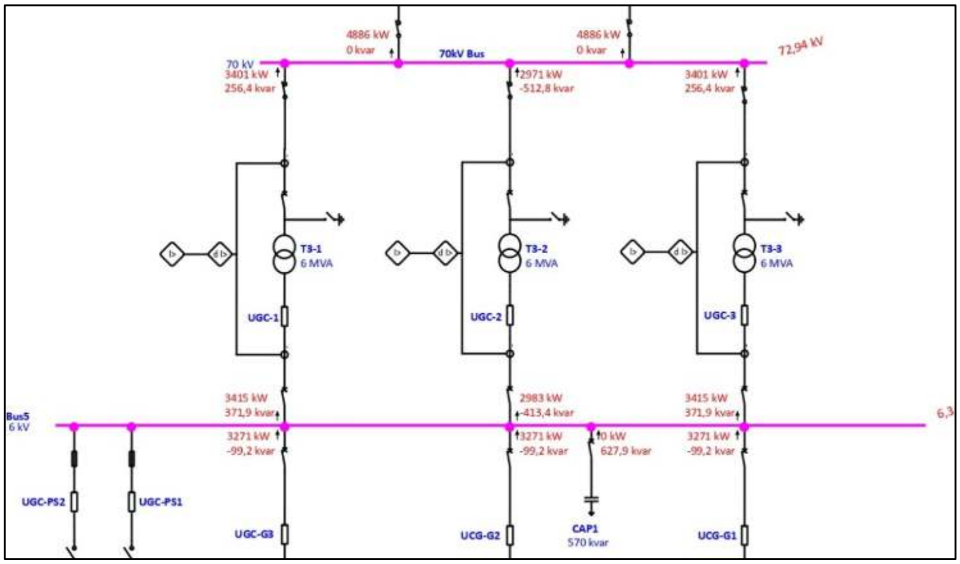

Figure 6. Simulation of capacitor bank implementation

In this scenario, a capacitor bank with a capacity of 569.9 kVar was installed on the secondary side of Main Transformer No. 2. Based on Table 5, the simulation results show that the kVar import value on the transformer decreased from –1342.9 kVar to –402.7 kVar. This indicates that the capacitor is capable of balancing ±70% of the reactive power previously imported. Additionally, there is an increase in the power factor value and a decrease in circulating current within the system.

Table 5. Results of the simulation of the capacitor bank addition to Siman Hydroelectric SLD using ETAP

ID	Type	kW Flow	kvar Flow	Amp Flow	% PF	% Loading
T3-1	Transf. 2W	3414,5	371,4	314,9	99,41	57,2
T3-2	Transf. 2W	2970,8	-512,8	23,86	-98,54	50,2
T3-3	Transf. 2W	3414,5	371,4	314,9	99,41	57,2

Addition of SOP for PMT Release during Standby

This approach does not require changes to the electrical system, but rather operational adjustments. SOPs (Standard Operating Procedures) are developed to ensure that the PMT (Power Breaker) on Main Transformer No. 2 is released when the unit is in standby mode and does not contribute to power generation. As shown in Figure 7, the simulation indicates that when the transformer is disconnected, the circulating current disappears, and the reactive power previously imported also vanishes, thereby eliminating additional costs due to kVar tariffs. Although operational in nature, this solution is highly effective for specific conditions and can be easily implemented without significant investment.

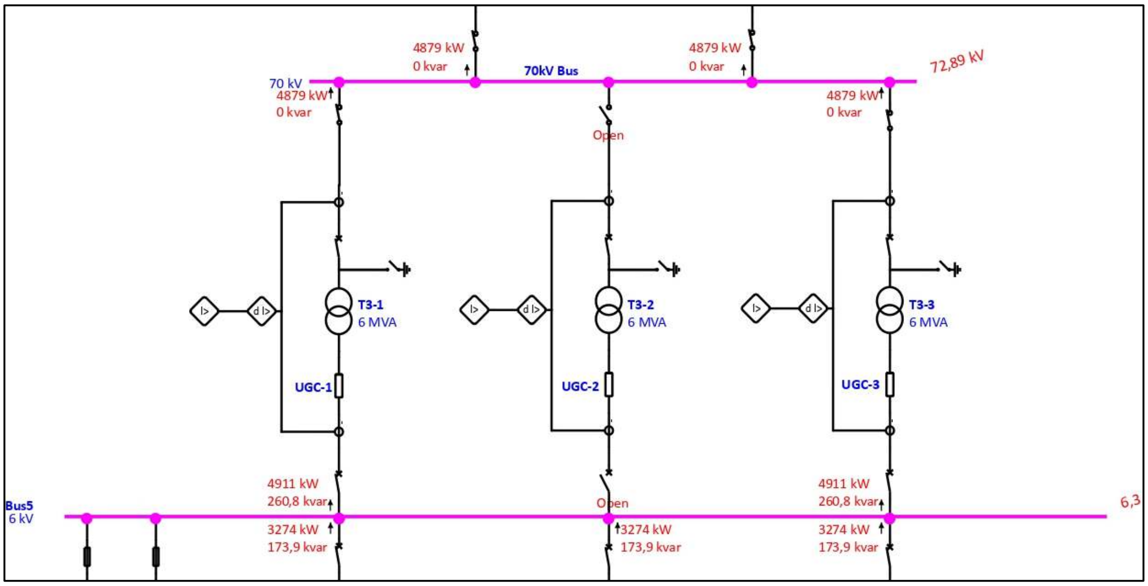

Figure 7**.** Simulation of the addition of SOP for the release of PMT transformer number 2 (T3-2)

This scenario models the condition where PMT Main Transformer No. 2 is operationally released when the unit is not operating (standby). According to Table 6, the simulation shows that when PMT is released, the import kVar value on the transformer becomes 0 kVar, because there is no reactive power flow to or from the transformer. The reduction in kVar import reaches 100% during standby conditions and does not affect system stability, as the load can be supported by the other two transformers.

Table 6**.** Results of the simulation of the addition of SOPs for the release of PMT SLD PLTA Siman

ID	Type	kW Flow	kvar Flow	Amp Flow	% PF	% Loading
T3-1	Transf. 2W	4910,1	259,9	450,9	99,86	81,9
T3-2	Transf. 2W	0	0	0	0	0
T3-3	Transf. 2W	4910,1	259,9	450,9	99,86	81,9

Replacement of Main Transformer number 2

This solution is a permanent corrective measure involving the replacement of Main Transformer No. 2 with one that has the same voltage ratio and impedance specifications as Main Transformers No. 1 and No. 3. Based on ETAP simulations, this replacement eliminates circulating currents, and the three transformers operate in a balanced manner in sharing the load and reactive power. Although it provides the best technical results, this solution has a high level of complexity and investment costs, so it requires strategic consideration from both technical and long-term operational perspectives.

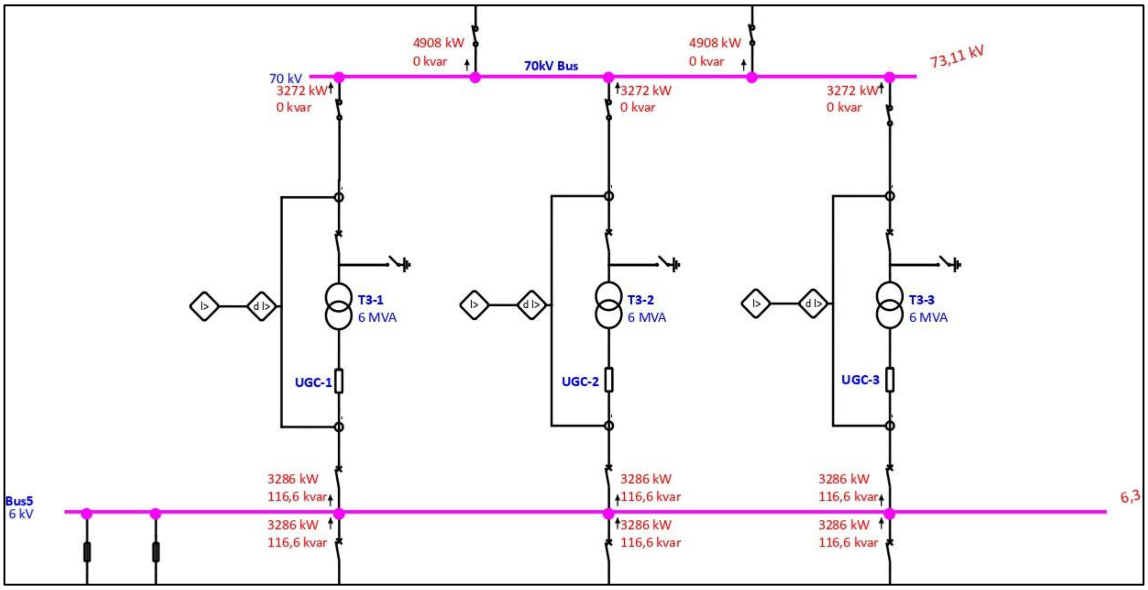

Figure 8. Simulation of the replacement of main transformer number 2 (T3-2)

In this scenario, Main Transformer No. 2 is replaced with a new transformer that has the same voltage ratio and impedance specifications as Main Transformers No. 1 and 3. Table 7 the simulation results show that the imported kVar value changes from –1342.9 kVar to +18.3 kVar, which means that the transformer no longer absorbs reactive power from the system but instead supplies it in a balanced manner. Additionally, the circulating current value disappears, and power distribution becomes proportional among the transformers.

Table 7. Results of the simulation of the replacement of transformer number 2

ID	Type	kW Flow	kvar Flow	Amp Flow	% PF	% Loading
T3-1	Transf. 2W	3285,7	116,2	301,5	99,94	54,8
T3-2	Transf. 2W	3285,7	116,2	301,5	99,94	54,8
T3-3	Transf. 2W	3285,7	116,2	301,5	99,94	54,8

Analysis of implementation results

Table 8 based on simulation results and technical analysis, three solutions are proposed to address the import kVar anomaly:

Table 8. Parameter values from simulation results of solution implementation

Solusi	Nilai awal (kVar)	Nilai akhir (kVar)	Pengurangan (kVar)	Efektivitas (%)
Application of Capacitor Banks	–1342,9	–402,7	940,2	70%
Addition of SOP for PMT Release during Standby	–1342,9	0	1342,9	100% (saat idle)
Replacement of Main Transformer	–1342,9	+18,3	1361,2	~100% (penuh)

The imported kVar value of Main Transformer No. 2 in its existing condition is –1342.9 kVar, indicating significant reactive power absorption due to parameter mismatch between transformers. Simulation results show that the implementation of the PMT release SOP is the simplest and most effective solution when the unit is in standby mode, as it does not have a negative impact on the system and is easy to implement. Meanwhile, the use of capacitor banks is a suitable technical approach for conditions where the transformer remains in active operation, with sufficiently high effectiveness in reducing the kVar import value. Replacing the transformer has proven to be the most ideal technical solution as it addresses the root cause of the problem, namely the mismatch in voltage ratios between transformers. However, from an implementation perspective, this solution requires significantly more effort and cost compared to the two previous alternatives. Considering operational conditions and the level of implementation complexity, a combined approach between PMT disconnection SOP and capacitor bank installation is deemed the optimal technical strategy without the need to replace the main equipment.

Discussion of research findings

The results of the identification show that the main cause of imported kVar is the mismatch in voltage and impedance ratios in Main Transformer No. 2 when compared to the other two transformers connected in parallel in the bus transformer system. This mismatch causes circulating currents between transformers, resulting in reactive power being absorbed back into the transformer (negative kVar) instead of being distributed to the network as it should be. Three technical solutions have been simulated and evaluated:

a) The installation of a 569.9 kVar capacitor bank can reduce kVar imports by up to ±70%, which is effective for operational conditions when the transformer is active. Capacitors provide local reactive power, thereby reducing reliance on external system supply.
b) The addition of an SOP for PMT disconnection when the standby unit is operational has reduced imported kVar by 100% when the unit is not in operation. This solution is considered the simplest, fastest to implement, and has no negative impact on system stability.
c) Replacing Main Transformer No. 2 with a new unit having the same voltage ratio as the other transformers results in the complete elimination of circulating current, with a change in kVar from –1342.9 to +18.3 kVar. However, this solution requires high implementation costs and time, as well as physical intervention in the infrastructure.

Based on the analysis results, it can be concluded that the combination of implementing PMT release SOPs and installing capacitor banks is the most effective and technically efficient approach to be implemented in the near future, without requiring replacement of major equipment. This solution can also improve operational efficiency, reduce reactive power losses, and avoid additional costs due to kVar import tariffs imposed by PLN.

4. Conclusion

This study successfully identified the root cause of the technical problem behind the kVar import anomaly that occurred in Main Transformer No. 2 at the Siman Hydroelectric Power Plant, which was caused by a mismatch in the voltage ratio and impedance between transformers in a parallel configuration. Based on technical simulations using ETAP, three solutions were tested to address the issue: installing a capacitor bank, implementing an SOP for PMT disconnection when the unit is in standby mode, and replacing the transformer with one that meets the appropriate specifications. The analysis results showed that each solution had different technical impacts. The installation of capacitor banks significantly reduced the kVar import value by approximately 70%, while the PMT disconnection SOP was effective when the unit was not in operation and did not require major system intervention. Transformer replacement provided the best technical results, but with higher implementation complexity and costs. Therefore, the most relevant and technically efficient solution is a combination of capacitor bank installation and operational SOPs, as both can be implemented with significant technical impact without replacing major equipment.

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