Power Transmission Optimization Using Synchronous Condenser Incorporated with Hybrid Particle Swarm Pattern Search Algorithm

Rishan Karangan
Department of Electrical Engineering
Hasanuddin University
Makassar, Indonesia
rishankarangan@gmail.com

Ardiaty Arief
Department of Electrical Engineering
Hasanuddin University
Makassar, Indonesia
ORCID: 0000-0002-1721-3948

Rhiza S. Sadjad
Department of Electrical Engineering
Hasanuddin University
Makassar, Indonesia
rhiza@unhas.ac.id

Muhammad Bachtiar Nappu
Department of Electrical Engineering
Hasanuddin University
Makassar, Indonesia
ORCID: 0000-0003-0406-5971

***Abstract*—The synchronous condenser (SC) was tested in this study to improve performance of the power transmission in the South Sulawesi Electric Power System model, in Indonesia, a multi-engine power system, using a hybrid of particle swarm optimization (PSO) and pattern search (PS) algorithms. This method employs MATLAB and DigSILENT, which is linked by an automated data exchange protocol. Power flow calculations are performed using DigSILENT, and the particle swarm pattern search optimization (PSPSO) algorithm is implemented using MATLAB. This method has been shown through power flow calculation to minimize losses on the transmission line and enhance voltage profile, ensuring power grid stability.**

Keywords— power optimization; synchronous condenser; artificial algorithm; MATLAB; DigSILENT

I. INTRODUCTION

Due to global environmental concerns on earth, coal-fired power plants (CFPP) and diesel-fired power plants (DFPP) have been converted in recent years to renewable energy generation, such as solar power plants (SPP) and wind power plants (WPP), that's called clean energy [1]. Despite having a significant impact on improving environmental conditions, the discontinuation of several CFPP and DFPP coupled with an increase in the number of SPP and WPP creates a new issue for electricity providers and regulators. For instance, a decrease in the transmission system's level of reliability, caused by a decrease in system inertia, which results in frequency instability, and a decrease in the network's short-circuit power [2]. Similar conditions exist in Indonesia, where the State-owned Electricity Company or in Indonesian, *Perusahaan Listrik Negara* (PLN), the sole electricity regulator, has not yet closed its CFPPs, but many diesel generators (DFPPs) have been laid off. With the increased development of SPP and WPP, system operators are now experiencing system instability issues as a result of reduced inertia and all of its derivative effects [3].

Up to this point, the problem of system instability caused by a lack of reactive power supply as a result of the proliferation of renewable energy plants has been addressed through the use of capacitor bank [4] and various flexible alternating current transmission system (FACTS) equipment such as static VAR compensator (SVC), and static synchronous compensator (STATCOM). However, such equipment is incapable of tackling the problem of system inertia [5]. One of the major drawbacks of using FACTS equipment is the emergence of harmonics, which reduces transmission system efficiency since harmonics cause overcurrent, extra losses, and noise in the telecommunications system [6]. With these considerations, synchronous condenser (SC) technology has been reborn, and its use to produce and absorb reactive power, increase power system inertia, and increase short-circuit current capacity without causing harmonics has been studied [2], [3], [5], [7]–[10].

SCs have been used in a variety of countries around the world, but this tool has yet to be implemented in Indonesia's electricity system, which is managed by PLN. As a result, when this tool is integrated into the system, it will be classified as a pioneer of innovation, given that special arrangements must always be made based on the very diverse characteristics of each electrical transmission system. This includes the test system, the Southern Sulawesi transmission system, which has its own set of characteristics and grid code.

To achieve the best results in this study, researchers will determine the placement of SCs in DIgSILENT software using the Newthon Raphson method and then optimize in MATLAB software using a combination method of the particle swarm optimization (PSO) and pattern search (PS) algorithm. The utilization of DIgSILENT and MATLAB softwares has been shown to produce excellent results [11]. In the realm of artificial algorithms, the PSO optimization method has been shown to provide the best quality solution with the fewest iterations. In fact, PSO has shorter computational times and can be applied to real-world power grid scenarios [12], [13]. The local optimization trap, which is a significant weakness of PSO, will be controlled by employing a second algorithm, namely PS algorithm. The PS algorithm's flexibility allows it to be integrated with heuristic algorithms such as PSO to perform global searches without the need for gradients and objective functions. The particle swarm pattern search optimization (PSPSO) algorithm will be created by combining these two methods.

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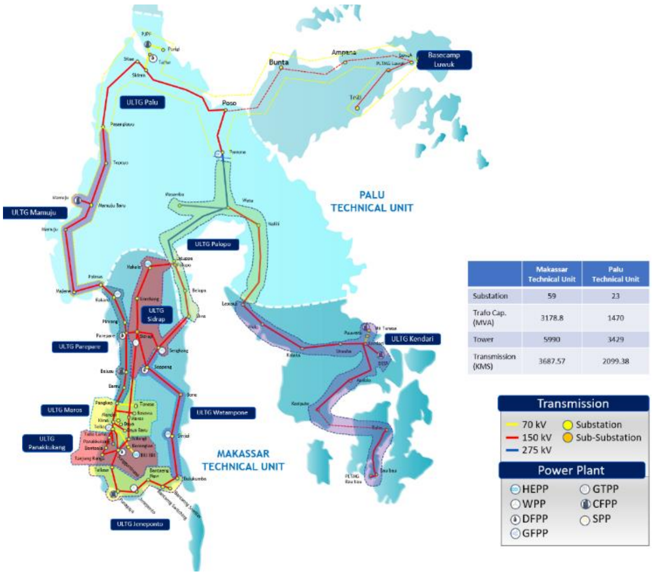
II. PROBLEM FORMULATION

A. Power System Model

The system used for analysis in this approach is the Southern Sulawesi power transmission system, as in Fig. 1 which is introduced for power network optimization studies. DigSILENT PowerFactory v15.1 is the tool used for modeling the power system and controllers for practical reasons. This software has a user interface and provides a simple alternative for power system modeling. DigSILENT also provides the option of analyzing power system performance via the load flow calculation module.



	Makassar Technical Unit	Palu Technical Unit
Substation	59	23
Trafo Cap. (MVA)	3178.8	1470
Tower	5990	3429
Transmission (KMS)	3687.57	2099.38

Fig. 1. Geographical map of the Southern Sulawesi Power Transmission System, based on report in [14]

B. Active Power Losses Objective Function

The primary purpose of the power grid optimization performed in this study is to reduce active power losses. The total sum of active power losses can be calculated using equation, as in (1).

$$F_{loss} = \sum_{k=1}^{N} g_k \left[V_{1,k}^2 + V_{2,k}^2 - 2V_{1,k}V_{2,k}\cos(\theta_{1,k} - \theta_{2,k})\right] \qquad (1)$$

The power transmission line conductance between starting and terminating buses is denoted by g_k. $V_{1,k}$ *and* $V_{2,k}$ are the starting and ending bus voltage magnitudes. $\theta_{1,k}$ *and* $\theta_{2,k}$ are the voltage angles of the starting and terminating buses. N denotes the number of transmission lines.

C. Voltage Deviation Constraint

In this approach, the reduction of voltage deviation is another important goal. Electrical equipment is built to perform best at its nominal voltage. Any deviation from the nominal voltage can reduce electrical equipment's overall effectiveness and longevity. The goal of voltage deviance constraint is to improve power system voltage profiles by minimizing the sum of voltage deviations at load buses. The voltage deviance constraint can be defined as accumulating the least amount of voltage deviation at each load bus. The following is the definition of this function:

$$V_D = \sum_{j=1}^{M} \left|V_j - V_j^{ref}\right| \qquad (2)$$

V_j is actual voltage of jth load bus. V_j^{ref} is ideal voltage of j^{th} load bus. M is number of load buses.

D. Voltage Stability Index

For simplicity, the voltage stability index can be defined as the ratio V/V_0, where V is the voltage magnitude of all *PQ* buses when loaded and V0 is the voltage magnitude of all *PQ* buses when not loaded. A voltage stability diagram for the respective bus is provided by the the V/V_0 ratio at each node, indicating weak spots that must be addressed by power system operators. There are numerous indices available for this purpose, with the current one being chosen for simplicity.

$$VSI = \sum_{i=1}^{T} \left|1 - \frac{V_i}{V_{i0}}\right| \qquad (3)$$

V_i is magnitude of voltage of ith *PQ* bus in the loaded state. V_{i0} is magnitude of voltage of ith PQ bus in the absence of load. T is losses on the transmission line (MW).

E. Constraints of Control and State Variables

The output capability of the reactive power compensators (C), the tap changer settings for all transformers (T), and the terminal voltage for all generators (V) are all included in the control variable constraints. The state variables are the voltage magnitude of all PQ buses (U) and the reactive power output from all generators (Q), that can be written as:

$$V_{Gk,min} < V_{Gk} < V_{Gk,max} \qquad (4)$$

$$T_{i,min} < T_i < T_{i,max} \qquad (5)$$

$$C_{j,min} < C_j < C_{j,max} \qquad (6)$$

$$Q_{Gk,min} < Q_{Gk} < Q_{Gk,max} \qquad (7)$$

$$V_{l,min} < U_l < V_{l,max} \qquad (8)$$

$V_{Gk,min}$ $(V_{Gk,max})$, $T_{i,min}$ $(T_{i,max})$, $C_{j,min}$ $(C_{j,max})$, $Q_{Gk,min}$ $(Q_{Gk,max})$ and $V_{l,min}$ $(V_{l,max})$ are lower (upper) boundary values of PV bus voltages, tap ratio of transformers, reactive power output of compensators, reactive power output of PV buses and voltage magnitude of load buses, respectively.

F. Equation of System Power Flow Constraint

The primary goal of the power grid optimization performed in this study is to reduce active power losses. The total sum of active power losses can be calculated using equation, as in (1). Punctuate equations with commas or periods when they are part of a sentence, as in:

$$P_{Gi} - P_{Li} - V_i \sum_{j=1}^{n} V_j \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij} = 0\right) \qquad (9)$$

$$Q_{Gi} - Q_{Li} - V_i \sum_{j=1}^{n} V_j \left(G_{ij}\sin\delta_{ij} + B_{ij}\cos\delta_{ij} = 0\right) \qquad (10)$$

where, n is number of buses, P_{Gi} and Q_{Gi} are generator active and reactive power of the i^{th} bus. P_{Li} and Q_{Li} are load active and reactive power of i^{th} bus. V_i and V_j are voltage magnitudes of ith and jth buses (two neighboring busbars). G_{ij}, B_{ij}, and δ_{ij} are conductance parameters and voltage angle between ith and j^{th} buses, respectively.

III. METHODOLOGY

This work combines the use of synchronous condensers (SCs) with hybrid artificial PSPSO to optimize power transmission. The existing system network is calculated using Newthon Raphson method in the DIgSILENT program to obtain initial data, and then sequentially optimized by installing synchronous condensers and applying PSPSO to reduce system losses. The following are the stages of the process:

1. Run power flow with Newthon Raphson method on the system model created in the DIgSILENT application. This step is completed to obtain data losses in the existing system, which will serve as a guide for SCs placement. SCs will be distributed to a location with the highest loss rate.
2. Deployed the SC on the system model created in the DIgSILENT application. The first step optimization is performed at this stage to reduce system losses by improving the system's reactive power.
3. Putting the PSO method into action using MATLAB. At this point, the system that has been optimized with SCs is re-optimized with the PSO method to obtain the lowest loss value, special arrangements for this algorithm are made based on research conducted in [15].
4. Similarly to step 3, we now put the PS algorithm into situation. At this point, the previously optimized system with SCs is re-optimized with the PS method to determine the value of losses, which is then compared to the value of the PSO results.
5. The PSPSO method is used. At this point, the SC-optimized system is re-optimized with the PSPSO artificial hybrid method to achieve maximum loss reduction.

The data used in this research is data obtained from the Indonesian’s State-owned Electricity Company (PLN) [14]. The data to be collected are bus and load data, transmission line data, and generator capacity data of the Southern Sulawesi power transmission system. Fig. 2 shows the flowchart of the deployed optimization method.

IV. SIMULATION RESULTS

The proposed method in this study combines the use of SCs with PSPSO hybrid artificial optimization to improve system performance, comparing the initial loss value of Newthon Raphson method with the results from using SCs, the PSO method, the PS method, and the PSPSO, respectively.

Because the data in Table I show that the Southern Sulawesi grid has a high power losses, the SCs in this study are distributed within that grid. The results of system transmission losses when SCs are used are shown in Table II.

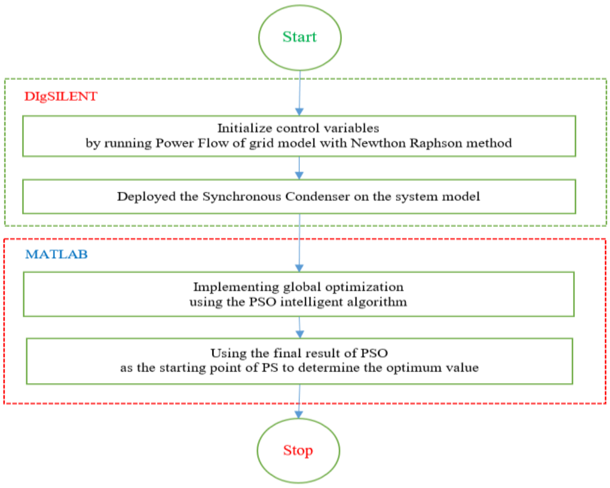


Fig. 2. Flowchart of the strategy using SCs incorpotated with hybrid artificial algorithm PSPSO

TABLE I. POWER TRANSMISSION LOSSES DATA FOR SOUTHERN SULAWESI POWER GRID USING SC

Active power losses (base condition)	56,446,400 (W)
Active power losses (after SCs installed)	54,840,000 (W)
Reduction ratio	2.85%

TABLE II. POWER TRANSMISSION LOSSES DATA FOR SOUTHERN SULAWESI POWER GRID USING PS ALGORITHM

Active power losses (before)	56,446,400 (W)
Active power losses (after)	53,288,500 (W)
Reduction ratio	5.59%
Elapsed optimization time	4,463.58 seconds

Once SCs have been successfully integrated into the system, it is time to optimize using intelligent algorithms. Derived from Fig. 3, the Table III depicts system performance after PS algorithm optimization. According to the data, the PS method reduced losses by 5.59% in a relatively short optimization time.

The PSO method, on the other hand, managed to achieve a loss reduction record of 6.18% despite taking longer than the PS method in terms of optimization time. Fig. 4 and Table IV displays the PSO optimization results.

TABLE III. POWER FLOW CALCULATION FOR SOUTHERN SULAWESI POWER SYSTEM USING NEWTHON RAPHSON METHOD

Grid Name	**Generation**		**Inter Grid Flow**		**Load**		**Grid Losses**	
	MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
Bantaeng	0.00	0.00	-202.85	-75.17	201.25	70.90	1.60	4.27
Kima-Daya Baru	0.00	0.00	-0.03	50.36	0.00	0.00	0.03	-50.36
PLTB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Smelter Bungku	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulsel	1,526.16	270.02	369.80	-73.49	1,112.55	207.79	43.81	5.59
Sulteng	13.97	1.00	-154.70	-4.63	163.53	18.08	5.14	-12.45
Sultra	149.00	36.80	-12.15	107.73	155.35	30.31	5.79	-101.24
Wotu-Masamba	0.00	0.00	-0.08	-4.81	0.00	0.00	0.08	4.81
Total	1,689.13	308.32			1,632.69	327.07	56.45	-149.38
*Installed Capacity 1,964.46 MW		**Spinning Reserve 160.67 MW						

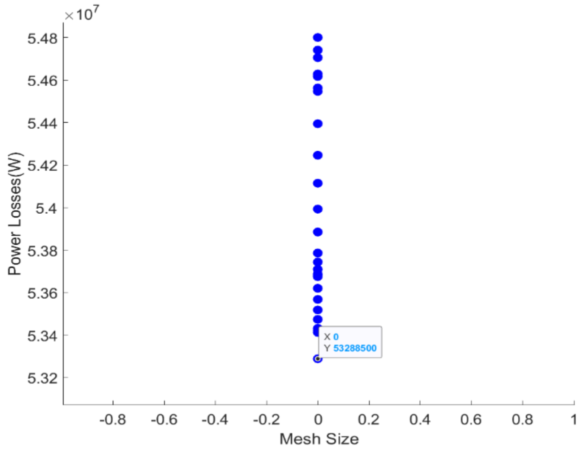


Fig. 3. Active power losses trend for Southern Sulawesi power system using PS algorithm

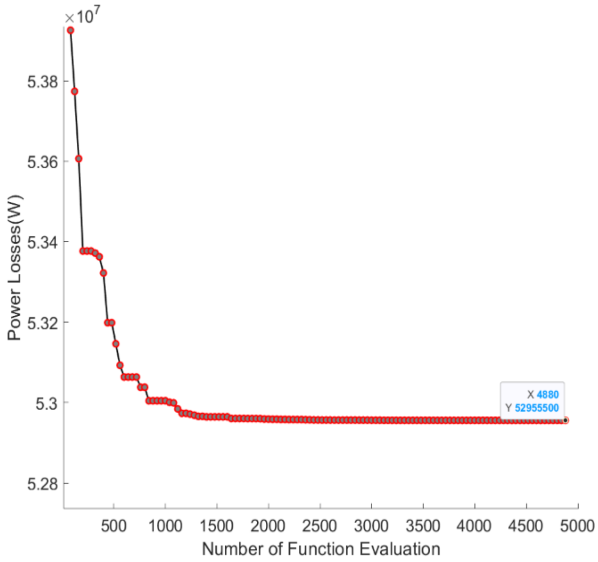


Fig. 4. Active power losses trend for Southern Sulawesi power system using PSO

TABLE IV. POWER TRANSMISSION LOSSES DATA FOR SOUTHERN SULAWESI POWER GRID PSO

Active power losses (before)	56,446,400 (W)
Active power losses (after)	52,955,500 (W)
Reduction ratio	6.18%
Elapsed optimization time	20,938.61 seconds

Fig. 5 and Table V provide the results of system optimization in the Southern Sulawesi power grid by combining the use of SCs with the PSPSO method that show the proposed method generates fewer losses than the initial conditions using the Newthon-Raphson method, as well as smaller losses than both the PS and PSO methods. Losses from the proposed method are reduced by 3,491,800 W, which is greater than the losses from the PS and PSO methods, which are reduced by 3,157,895 W and 3,490,851 W, respectively.

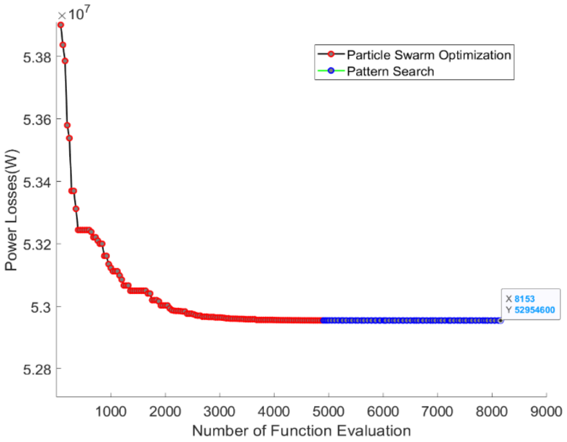


Fig. 5. Active power losses trend for Southern Sulawesi power transmission using PSPSO algorithm

TABLE V. POWER TRANSMISSION LOSSES DATA FOR SOUTHERN SULAWESI POWER GRID PSPSO

Active power losses (before)	56,446,400 (W)
Active power losses (after)	52,954,600 (W)
Reduction ratio	6.19%

Considering Fig. 5, 6, 7, and Tables V, VI, VII, the PSPSO method is a significant improvement in the operational parameters. Active power losses fell from 56,446,400 to 52,954,600 (W). As shown in Table VI, for undervoltage substations, the total value of the system stability index has increased from 7.70 to 7.74, while the total value of the voltage deviation has decreased dramatically from -34,894.30 V to -3,059.47 V. In light of this, Table VII demonstrates that at substation overvoltage, the total system stability index value increases from 37.36 to 37.39 and the total voltage deviation value decreases slightly from 230,370.46 V to 222,923.37 V. Furthermore, all voltage deviations can be minimized to adhere to the percentages permitted by the Sulawesi grid code.

TABLE VI. VOLTAGE DEVIATION AND VOLTAGE STABILITY DATA FOR SOUTHERN SULAWESI POWER GRID USING PSPSO

Substation Name	**Voltage Stability Index**		**Voltage Deviation (V)**			
	Before Optimization	**After Optimization**	**Before Optimization**	**%[a]**	**After Optimization**	**%[a]**
Bantaeng Smelter	0.94	0.95	-7,214.69	-4.81	-2,925.85	-1.95
Bantaeng Switching	0.95	0.95	-7,062.22	-4.71	-2,781.19	-1.85
Bulukumba	0.95	0.95	-6,812.08	-4.54	-2,647.06	-1.76
Bantaeng	0.95	0.96	-5,314.47	-3.54	-921.89	-0.61
Sinjai	0.97	0.97	-4,995.74	-3.33	-1,620.21	-1.08
Jeneponto	0.97	0.97	-2,247.72	-1.50	2,287.39	1.52
Bone	0.99	1.00	-1,212.90	-0.81	1,309.61	0.87
Panakkukang	0.98	0.98	-34.48	-0.02	4,239.73	2.83
Total	7.70	7.74	-34,894.30		-3,059.47	
Difference 0.04			Difference (V) 31,834.83			

[a] Range of allowable voltage variation of 275 kV and 150 kV according to Sulawesi's grid code between +10% and 10%.

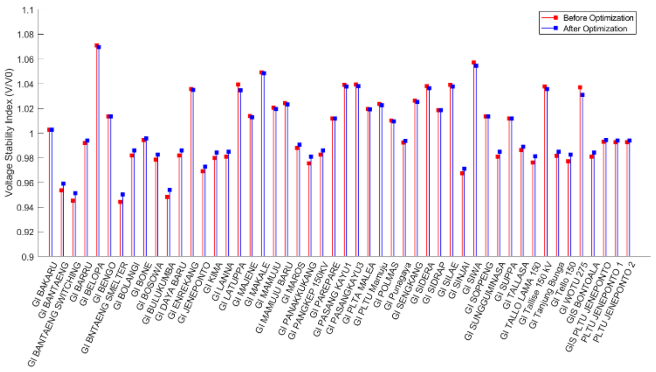


Fig. 6. Voltage stability index for Southern Sulawesi power grid using PSPSO algorithm

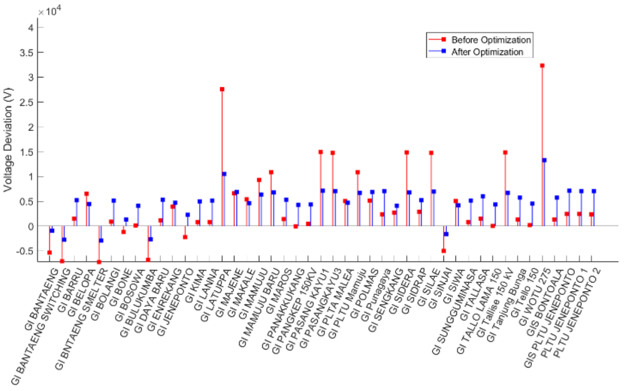


Fig. 7. Voltage deviation for Southern Sulawesi power grid using PSPSO algorithm

TABLE VII. VOLTAGE DEVIATION AND VOLTAGE STABILITY DATA FOR SOUTHERN SULAWESI POWER SYSTEM USING PSPSO

Substation Name	**Voltage Stability Index**		**Voltage Deviation (V)**			
	Before Optimization	**After Optimization**	**Before Optimization**	**%[b]**	**After Optimization**	**%[b]**
Tallo Lama	0.98	0.98	47.40	0.03	4,317.70	2.88
Bosowa	0.98	0.98	70.09	0.05	4,105.45	2.74
Tello	0.98	0.98	236.47	0.16	4,500.60	3.00
Pangkep	0.98	0.99	432.97	0.29	4,313.83	2.88
Kima	0.98	0.98	793.80	0.53	4,961.57	3.31
Lanna	0.98	0.99	821.74	0.55	5,132.80	3.42
Sungguminasa	0.98	0.99	828.93	0.55	5,140.19	3.43
Bolangi	0.98	0.99	914.66	0.61	5,164.31	3.44
Daya Baru	0.98	0.99	1,130.44	0.75	5,263.36	3.51
Bontoala	0.98	0.98	1,295.45	0.86	5,752.96	3.84
Tanjung Bunga	0.98	0.99	1,299.69	0.87	5,748.65	3.83
Maros	0.99	0.99	1,420.09	0.95	5,301.29	3.53
Tallasa	0.99	0.99	1,457.20	0.97	5,963.92	3.98
Barru	0.99	0.99	1,517.10	1.01	5,180.73	3.45
Punagaya	0.99	0.99	2,357.54	1.57	7,045.12	4.70
Jeneponto 2	0.99	0.99	2,399.91	1.60	7,073.04	4.72
Jeneponto	0.99	0.99	2,415.25	1.61	7,068.29	4.71
Pltu Jeneponto	0.99	0.99	2,464.72	1.64	7,088.04	4.73
Sengkang	1.03	1.03	2,728.98	1.82	4,069.60	2.71
Sidrap	1.02	1.02	2,886.18	1.92	5,182.44	3.45
Enrekang	1.04	1.04	3,904.48	2.60	4,667.45	3.11
PLTA Malea	1.02	1.02	5,016.42	3.34	4,687.71	3.13
Siwa	1.06	1.06	5,048.50	3.37	4,157.94	2.77
Polmas	1.01	1.01	5,172.02	3.45	6,864.75	4.58
Makale	1.05	1.05	5,435.17	3.62	4,624.81	3.08
Belopa	1.07	1.07	6,540.64	4.36	4,433.21	2.96
Majene	1.01	1.01	6,583.56	4.39	6,853.15	4.57
Mamuju	1.02	1.02	9,284.46	6.19	6,309.72	4.21
Mamuju Baru	1.02	1.02	10,843.27	7.23	6,785.33	4.52
PLTU Mamuju	1.02	1.02	10,886.36	7.26	6,719.85	4.48
Pasangkayu	1.04	1.04	14,771.39	9.85	7,005.90	4.67
Silae	1.04	1.04	14,774.71	9.85	6,973.35	4.65
Tallise	1.04	1.04	14,834.99	9.89	6,718.59	4.48
Sidera	1.04	1.04	14,867.86	9.91	6,757.55	4.51
Pasang Kayu	1.04	1.04	14,963.97	9.98	7,153.65	4.77
Latuppa	1.04	1.03	27,601.47	1.04	10,543.66	3.83
Wotu	1.04	1.03	32,322.58	11.75	13,292.86	4.83
Total	37.36	37.39	230,370.46		222,923.37	
	Difference 0.03		Difference (V) 7,447.09			

[b] Range of allowable voltage variation of 275 kV and 150 kV according to Sulawesi's grid code between +10% and -10%.

The power flow results of the Southern Sulawesi power system revealed that the proposed method outperformed the initial condition and the other two methods, PS and PSO. The introduction of SCs to the system reduced power losses by up to 1,606,400 W. The value of transmission losses can be reduced even further with the addition of PSPSO optimization to 3,491,793 W.

V. CONCLUSIONS

Based on the simulation results presented in this paper for the Southern Sulawesi power system, it is possible to conclude that:

1. The introduction of SCs to the system improved system performance by reducing active power losses and enhance the voltage profile, ensuring power grid stability.
2. The PSO method produces a better loss value than the PS method, but the PS method outperforms in terms of optimization time efficiency.
3. The total power losses and voltage obtained by applying the proposed PSPSO method to the SCs-optimized system in the Southern Sulawesi power system were lower than the PS and PSO methods. The total power losses obtained are 3,491,793 W.
4. The PSPSO method significantly improves operational parameters, particularly in terms of increasing the voltage stability index and minimizing voltage deviation to comply with the grid code rules.

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