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Harmonic Distortion Mitigation with Single Tuned Filter in ULP Sungguminasa Using Whale Optimization Algorithm

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***Abstract*—The spread of harmonic distortion in a distribution electricity system is a problem that can reduce system performance in terms of power quality. This can cause losses to equipment damage. This study attempts to optimize the placement and size of single tuned filters at harmonic orders 5, 7, 11, 13, 17 using the Whale Optimization Algorithm (WOA) method which has been validated in the electricity system of ULP Sungguminasa PT. PLN (Persero) with the objective function of minimizing total losses. the maximum optimization results were obtained in the form of placement and filter size at order 5 of 5081.22 kVAr on bus 83 capable of reducing total losses by up to 28.05% compared to the location and size of single tuned filters in other orders and the %THDv value was able to be reduced to the allowable limit.**

Keywords—Single Tuned Filter, Harmonic Distortion, ULP Sungguminasa, WOA, Power Quality.

I. Introduction

Behind the benefits of radial distribution systems, these systems are highly susceptible to harmonic propagation. With the increasing use of non-linear loads driven by technological advancements, power quality has become a prevalent issue [1]. The penetration of harmonics can lead to decreased efficiency of power system components, excessive equipment heating, insulation stress, and disruptions in communication systems [2]. These undesirable impacts not only affect voltage profiles but also result in power losses. The most severe consequences of harmonics occur when the existing harmonics exceed the IEEE 519-1992 standard, potentially causing permanent damage to electrical equipment [3].

The harmonic source generates a non-sinusoidal current characterized by periodic waveforms that do not follow a sinusoidal shape and contain harmonics [4]. Nonlinear loads are the primary cause of high current harmonics in the system, which can lead to increased power losses in the distribution system and potential equipment damage [5]. Among the various technical options available to reduce harmonic distortions and improve power quality, the implementation of shunt capacitors to compensate for load power factor appears to be an important method for compensating current and voltage disturbances in power distribution systems. [6].

Consider the classical technique to find out the spread of harmonic distortion due to the use of nonlinear loads only on the basic components and does not take into account the interactions between them through the power distribution network [7]. Bus voltage, current, and line power loss are obtained by using the Forward Backward Sweep Method at fundamental frequency conditions. %THDv, %THDi and channel power loss for each harmonic order were obtained using the Harmonic Load Flow method. Harmonic Load Flow is an excellent method for assessing and analyzing the propagation of harmonic distortion in distribution systems especially in industrial areas [8]-[10].

The development of several optimization techniques in improving system performance in the form of improving power quality, especially mitigating the spread of harmonic distortion [11]-[13]. One of them is the passive harmonic filter, namely the single tuned filter. This type of filter has been widely used in industry to mitigate the spread of harmonics [14]. This is because the filter is very simple to operate. However, the placement of the size and location of the filter that is not suitable can bring losses and decrease the performance of the electrical system [15]. Minimizing the total line loss, improving bus voltage, decreasing the value of %THDv as one of the harmonic distortion parameters to the permissible limits with the placement of the size and location of the single tuned filter requires the best planning so that the planned objective function can be achieved [16]. There are several intelligence-based optimization methods that are considered capable of determining an optimization engineering plan so that effective and efficient results are obtained in finding the objective function with predetermined constraints [17].

The use of several methods based on artificial intelligence has been used to determine the location and size of the single tuned filter, among others, the Whale Algorithm Optimization (WOA) method tested on the IEEE 13-bus was able to reduce the total power loss by 34.26% [18], the Particle Swarm Optimization (PSO) method was tested on the IEEE-33 bus to reduce the total power loss to 23.46% [19], the Ant Colony Optimization (ACO) method was able to reduce the %THDv value below 5% on the IEEE 33-bus [14] , and Pareto Optimal Fronts (POF) gives results in the form of the amount of network losses, bus voltage profile, and the network harmonic distortion which is more efficient than the previous condition [17]. This research tries to apply the use of the WAO method in determining the size and location of a single tuned filter with the objective function of minimizing the total active power loss with predetermined constraints. This research will be tested on the PT PLN (Perseroi) ULP Sungguminasa 165-bus distribution electrical system at harmonic frequencies of the 5th, 7th, 11th, 13th and 17th order harmonics based on the MATLAB 2018b programming.

II. PROMBLEM SOLUTION

A. Objective Function (OF)

The purpose of this research is to find a objective function in the form of Minimal total power losses (P_{Loss}).

$$OF = P_{Loss} = P_{Loss^1} + \sum_{h=h_0}^{h_{max}} P_{Loss}{}^{(h)} \tag{1}$$

B. Constrain

To obtain the optimum position and size of the single tuned filter, the RMS voltage and THD level should be kept within reasonable limits. Therefore, the objective function requires equality and inequality constraints. Equality constraints are related to nonlinearities in power flow calculations. Inequality constraints consist of bus voltage, THD level, and reactive power injected by the filter. The constraints given to achieve the most efficient optimization are:

- Voltage of each bus

$$V_{min} \leq |V_i| \leq V_{max} \tag{2}$$

- Total Harmonic Distortion Limit
  THD level of each bus is less than or equal to 5%. Based on IEEE standard 519-1992.

$$THD_i(\%) \leq THD_{max} \tag{3}$$

- Reactive Power
  The reactive power supplied by the filter must not exceed the total reactive power demand in the system.

C. Single Tuned Filter Design

The following outline the sequential steps in the design process of a single tuned filter for a radial distribution system:

1. Step 1. Determine X_c and C in condition fundamental frequency

$$X_c = \frac{V^2}{Q_{filter}} \tag{4}$$

$$C = \frac{1}{2\pi f X_c} \tag{5}$$

2. Step 2. Specifies X_L and L at tuning frequency

$$L = \frac{1}{C(2\pi f_{tun})^2} \tag{6}$$

$$X_L = 2\pi f L \tag{7}$$

3. Step 3. Calculate the R value for Q quality

$$R = \frac{X_n}{Q} \tag{8}$$

$$X_n = \sqrt{\frac{L}{C}} \tag{9}$$

From the single tuned filter design step above, get the impedance from the filter;

$$Z_{filter} = R + j(X_L - X_c) \tag{10}$$

Thus, the harmonic frequency of the h impedance of the single tuned filter is;

$$Z_{filter}{}^{(h)} = R^{(h)} + j\left(X_L{}^{(h)} - X_c{}^{(h)}\right) \tag{11}$$

III. HARMONIC POWER FLOW

When developing harmonic power flow studies in electrical systems, Teng introduced the Harmonic Power Flow (HPF) algorithm. This algorithm is intended to accurately calculate and analyze the harmonic distribution in the system. The introduction of Teng's HPF algorithm has greatly contributed to the advancement of harmonic analysis techniques in the field of electrical engineering [8].

Figure 1 shows a distorted 6-bus radial distribution system (RDS). Harmonic distortion will occur. A harmonic source and passive filter are implemented on bus 4 to mitigate the effects of this harmonic distortion.

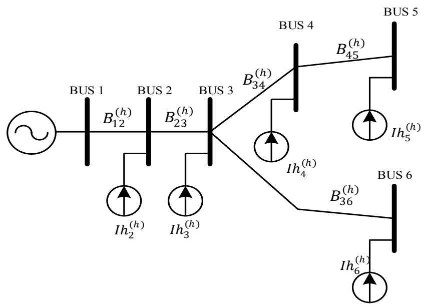

Figure 1. Single line diagram of distorted 6-bus RDS

In the system, the harmonic current absorbed by the filter at bus 4 can be calculated and expressed as follows:

$$\left[Is^{(h)}\right] = \left[Is_4{}^{(h)}\right] \tag{12}$$

The h^{th} harmonic current through the branches can be expressed as :

$$\left[I^{(h)}\right] = \left[h^{(h)} \ldots Is^{(h)}\right]^T \tag{13}$$

$$\left[B^{(h)}\right] = \left[A^{(h)}\right]\left[I^{(h)}\right] \tag{14}$$

For example, the h^{th} harmonic branch current for branches 3-4 can be determined using the following equations:

$$\left[B_{34}{}^{(h)}\right] = [A_{34}]^T\left[I^{(h)}\right] \tag{15}$$

The branch 3-4 coefficient vector is defined as:

$$\left[A_{34}{}^{(h)}\right] = \left[\,Ah_{34}{}^{(h)} \ldots As_{34}{}^{(h)}\right]^T \tag{16}$$

The coefficient vector $\left[A_{34}{}^{(h)}\right]$of branch 3-4 reflect the harmonic currents impact of nonlinear and linear loads..

The bus harmonic voltage can be calculated by Kirchhoff's Voltage Law (KVL) and the voltage of forward sweep method. The equation for the calculation ie:

$$\left[V^{(h)}\right] = \left[HA^{(h)}\right]\left[I^{(h)}\right] \tag{17}$$

where $\left[V^{(h)}\right]$ is the harmonic bus voltages vector and matrix $\left[HA^{(h)}\right]$ represents the interrelationship the harmonic bus voltages and currents. The harmonic voltage of the filter placed at bus 4 is determined by:

$$\left[V_{S_4}{}^{(h)}\right] = \left[\,HA_s{}^{(h)}\right]\left[I^{(h)}\right] \tag{18}$$

$\left[\,HA_s{}^{(h)}\right]$is the row vectors of the matrix $\left[HA^{(h)}\right]$ associated with the bus at which the filter is placed. The harmonic voltage of the filter placed at bus 4 in terms of its harmonic impedance is given as follows:

$$V_{S_4}{}^{(h)} = -Is_4{}^{(h)}\, x\, Zs_4{}^{(h)} \tag{19}$$

The harmonic bus voltage is calculated iteratively until it reaches a predefined tolerance as follows:

$$\left|V_i^{(h),k+1} - V_i^{(h),k}\right| \le \varepsilon \quad (20)$$

$V_i^{(h),k+1}$ is the harmonic voltage of bus i^{th} at the $(k+1)^{\text{th}}$ iteration, and $V_i^{(h),k}$ is the harmonic voltage of bus i^{th} at the k^{th} iteration.

$$Ploss^{(h)} = \sum_{i=1}^{6} Ploss_i^{(h)} = \sum_{i=1}^{6} \sum_{h=h_0}^{h_{max}} \left|B_i^{(h)}\right|^2 . R_i^{(h)} \quad (21)$$

$$Ploss^{(h)} = \left[R^{(h)}\right]^T . \left[A^{(h)}\right]\left[I^{(h)}\right]^2 \quad (22)$$

$R^{(h)}$ is the total branch resistance for the h^{th} harmonic order. The rms value of the bus voltages V_{rms_i} can be obtained from the harmonic bus voltages calculated for all harmonic frequencies using the method described above, and can be expressed as follows:

$$V_{rms_i} = \sqrt{\left|V_i^{(1)}\right|^2 + \sum_{h=h_0}^{h_{max}} \left|V_i^{(h)}\right|^2} \quad (23)$$

Finally, the total harmonic distortion at bus i can be calculated using the following equation:

$$THD_i(\%) = \sum\nolimits_{h=h0}^{h_{max}} \left|V_i^{(1)}\right|^2 / \left|V_i^{(1)}\right|^2 \quad (24)$$

IV. Whale Optimization Algorithm (WOA)

The Whale Optimization Algorithm (WOA) is a nature-inspired optimization algorithm developed based on the foraging behavior of humpback whales. In 2016, it was introduced by S. Mirjalili and A. Lewis. This algorithm mimics a hunting strategy known as bubble-net feeding that humpback whale use to trap prey. This spiral cellular web feeding operation can be described mathematically in two stages: *Searching and encircling the prey*, and *Spirally updating position* [20]-[21].

A. Searching and Encircling Prey

The process of humpback whales searching for prey can be mathematically modeled using the following equations:

$$D = |C . X_{rand} - X| \quad (25)$$

$$X(t+1) = X_{rand} - A . D \quad (26)$$

$$A = 2 . a . r - a \quad (27)$$

$$C = 2 . r \quad (28)$$

Prey siege can be expressed mathematically using the following equation: where the coefficient 'a' decreases linearly from 2 to 0 through the iterations and 'r' is a random number in between [0, 1]:

$$D = |C . X^*(t) - X(t)| \quad (29)$$

$$X(t+1) = X^*(t) - A . D \quad (30)$$

B. Spirally Updating Position

This approach starts by looking at the distance between the nearest whale location X, Y and its prey at X*, Y*. A spiral equation is then formed between the whale and prey positions to mimic the spiral motion of a humpback whale, as described in the following equation:

$$X(\text{t}+1) = D . e^{bl} . \cos(2\pi l) + X^*(\text{t}) \quad (31)$$

$$X(t+1) = \begin{cases} X^*(t) - A . D & if \quad p < 0{,}5 \\ D . e^{bl} . \cos(2\pi l) + X^*(\text{t}) & if \quad p \ge 0{,}5 \end{cases} \quad (32)$$

C. Optimization Using WOA

The steps of WOA namely:

1. Step 1: Initialization search agents for optimization, the impedance, load data, and the injected harmonic current.
2. Step 2: Using the FBS method, the HLF approach is employed to get the fundamental losses, losses of harmonic, THD, and rms voltage.
3. Step 3: Ensure search agents do not exceed predefined limits by including appropriate limits.
4. Step 4: Initialization the counter of iterations
5. Step 5: Calculate the fitness function and obtain the initial best agent.
6. Step 6: For every search agent, the values of *a, A, C, l,* and *p* are updated, where *l* and *p* are randomly generated numbers.
7. Step 7: If $(p < 0.5)$, proceed to Step 8. Otherwise, proceed to step 10.
8. Step 8: If $|A| < 1$, Update the position of the current search agent by applying equation (13).
9. Step 9: If $|A| \ge 1$, Calculate the new search agent and update its position using equation (17).
10. Step 10: Apply formula (19) to update the current search agent position.
11. Step 11: If the maximum number of iterations is reached, go to step 12. Otherwise, return to step 5.
12. Show the optimal solution

The step of research carried out can be seen in Figure 2.

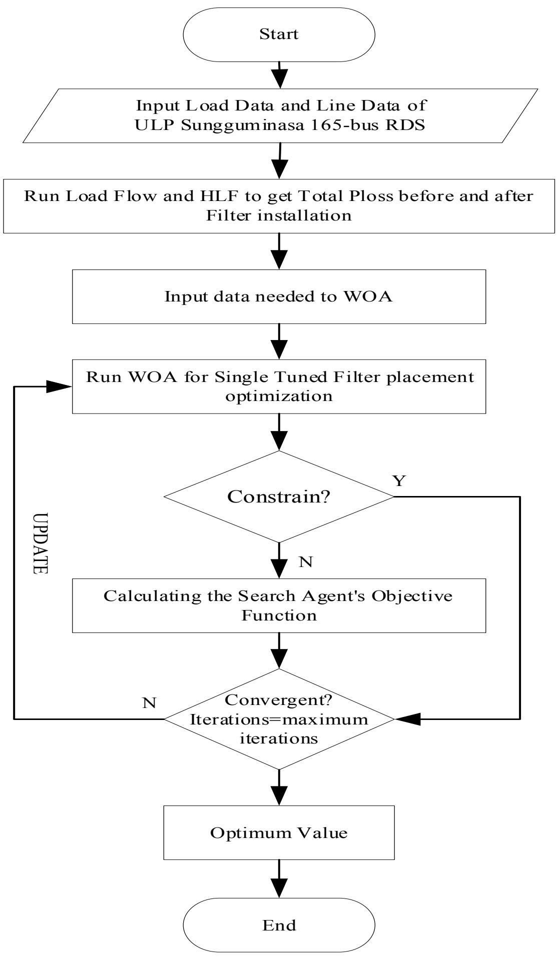

Figure 2. Step of the research.

D. ULP Sungguminasa and Study Case

ULP Sungguminasa is an electric distribution system located in Sungguminasa, South Sulawesi, Indonesia. The system serves as part of the electricity infrastructure to meet the power demands of the area. ULP Sungguminasa supplies electricity to residential, commercial, and industrial customers in the surrounding vicinity. The system is designed based on a radial distribution network configuration, which is widely used in power distribution systems.

- The Harmonic Source will be injected on several buses randomly until the %THDv value exceeds the allowable limit.
- Harmonic Source

Harmonic source will be supplied to the load bus for the purpose of generating harmonic propagation in the radial distribution system, as can be seen in Table 1.

TABLE 1. INJECTION OF HARMONIC SOURCE IN LOAD BUS

Orde	Magnitude (%)	Angle
5	98	140
7	39.86	113
11	18.95	-158
13	8.79	-178
17	2.5	-94

- Study Case

This research conducts a simulation of several scenario to determine the effect of optimization placement and sizing to find the objective function such as;

1) Scenario 1 (S-1). Normal Case
2) Scenario 2 (S-2). Optimal Single Tuned Filter on 5th Harmonic orde.
3) Scenario 3 (S-3). Optimal Single Tuned Filter on 7th Harmonic orde.
4) Scenario 4 (S-4). Optimal Single Tuned Filter on 11th Harmonic orde.
5) Scenario 5 (S-5). Optimal Single Tuned Filter on 13th Harmonic orde.
6) Scenario 6 (S-6). Optimal Single Tuned Filter on 17th Harmonic orde.

V. RESULT AND DISCUSSIONS

The proposed method explained is programmed in MATLAB R2018b and tested on radial distribution ULP Sungguminasa. The result obtained is explained in the following sections. The single line diagram of the 165-bus ULP Sungguminasa PT. PLN (Persero) can be seen in Figure 3. The slack bus is bus 1 and the other buses is Load bus. There are 105 load bus point on the load bus. The emergence of the spread of harmonic distortion after injection of harmonic currents originating from nonlinear loads on several load buses. The results of optimizing the placement and size of the single tuned filter based on several scenarios to find the objective function in the form of reducing total power losses within predetermined limits in improving power quality in the form of mitigating the spread of harmonic distortion using the WOA algorithm. Optimization results can be seen in table 2 and figure 4 and figure 5.

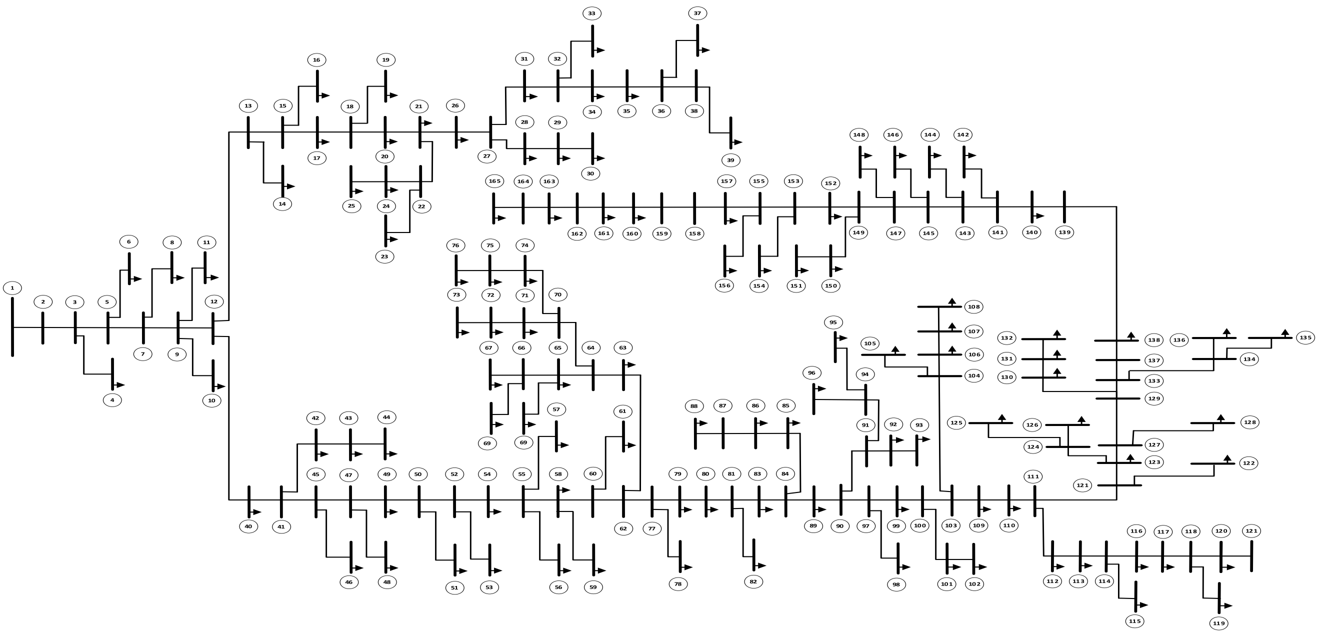

Figure 3. ULP Sungguminasa 165-bus RDS.

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In table 2, optimization results using the given WOA in determining the location and size of the filter at frequencies of order 5, 7, 11, 13 and 17 give different results in finding the objective function. The location and size of the filter serves to mitigate harmonic distortion based on the harmonic order. of the five existing scenarios. Placement of a filter on bus 83 with a size of 5081.2 kVAr in scenario 2 is able to reduce total losses by 28.05%, Placement of a filter on bus 116 with a size of 2102.0 kVAr in scenario 3 is able to reduce total losses by 13.63%. Placement of a filter on bus 78 with a size of 2875.9 kVAr in scenario 4 is able to reduce total losses by 8.56%. Placement of a filter on bus 77 with a size of 3511.9 kVAr in scenario 5 is able to reduce total losses by 8.66% and placement of a filter on bus 89 with a size of 2929.5 kVAr in scenario 6 is able to reduce total losses by 10.32%.

TABLE 2. OPTIMIZATION RESULT USING WOA

	S1	S2	S3	S4	S5	S6
Sizing (kVAr)	-	5081.2	2102.0	2875.9	3511.9	2929.5
Loc	-	83	116	78	77	89
***P**loss* **Fund (kW)**	315.31	241.38	282.57	289.14	289.32	301.36
***Q**loss* **Fund (kVAr)**	370.52	283.06	329.75	336.24	334.77	347.07
$Ploss^{(h)}$ (kW)	49.41	27.62	53.48	49.98	49.33	55.89
$Qloss^{(h)}$ (kVAr)	362.90	173.81	352.42	348.66	354.67	471.95
Total *P*loss (kW)	364.72	269.00	336.05	339.12	338.66	357.25
Total *Q*loss (kVAr)	733.42	456.87	682.18	684.91	689.45	819.02
***P*loss Impv (%)**	-	28.05	13.63	8.56	8.66	10.32
***Q*loss Impv (%)**	-	45.09	11.37	-4.53	-7.40	-12.39

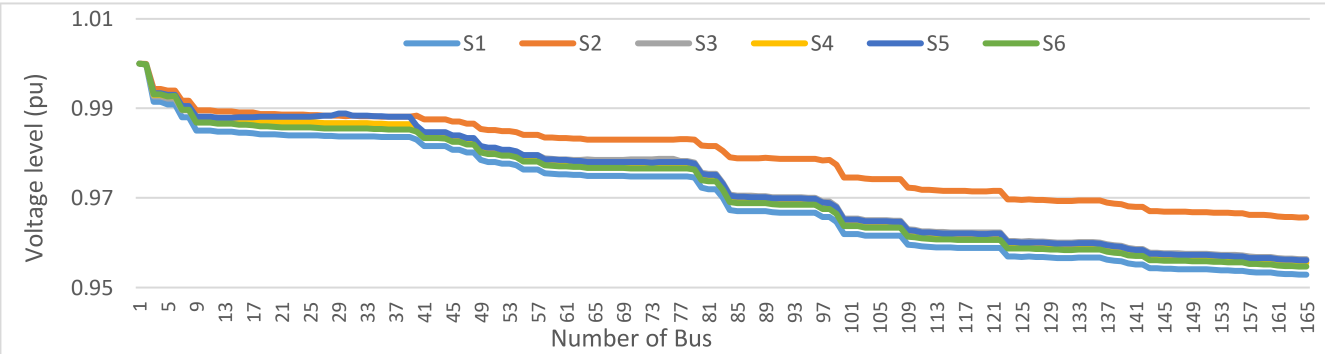

Figure 4. Comparison of voltage level bus in each scenario.

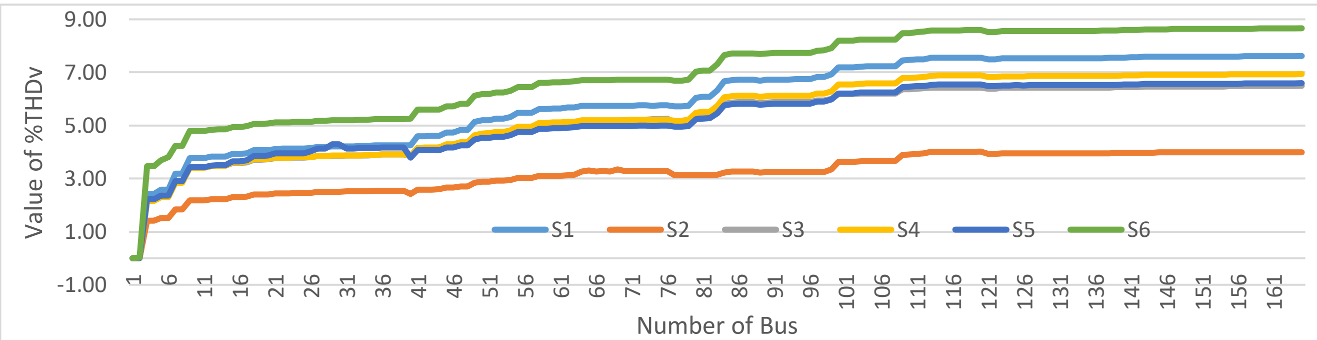

Figure 5. Comparison value of %THDv in each scenario.

Figure 4 shows a comparison of the bus voltage level in each scenario. The most effective results are seen in scenario 2 with an increase in the voltage level value of 0.95%. Not only the improvement in the bus voltage level, but also the best %THDv value improvement in scenario 2. This can be seen from Figure 5. The %THDv value has decreased to a predetermined limit compared to the other scenarios. Decrease in the value of %THDv with an average of 46.36%.

VI. CONCLUSION

P The use of WOA in determining the location and size of the single tuned filter to reduce total losses within the limits specified in the Sungguminasa ULP 165-bus radial distribution system PT. PLN (Persero) was considered effective in improving system performance. From the several scenarios that have been carried out, scenario 2 in the form of the placement and size of a single tuned filter designed at the 5th harmonic order gives the most effective results compared to other scenarios. Placement of a single tuned filter of 5081.2 kVAr on bus 83 gives an increase in total power losses of 28.05%. In addition, there is an improvement in the value of the voltage level at each load bus with an average increase of 0.95% and mitigation of the spread of harmonics, especially in the 5th order of harmonics with an average decrease in the %THDv value of 46.36% to the allowable limit. Subsequent research will discuss the effect of nonlinear load types on the amount of harmonic injection currents in electrical systems with household loads and industrial loads which will then be continued to optimize several optimization techniques that have been carried out in previous research [11],[12],[13].

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