Coordinated planning in improving power quality considering the use of nonlinear load in radial distribution system

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Article Info	ABSTRACT
	Power quality has an important role in the distribution of electrical energy. The use of non-linear load can generate harmonic spread which can reduce the power quality in the radial distribution system. This research is in form of coordinated planning by combining distributed generation placement, capacitor placement and network reconfiguration to simultaneously minimize active power losses, total harmonic distortion (THD), and voltage deviation as an objective function using the particle swarm optimization method. This optimization technique will be tested on two types of networks in the form 33-bus and 69-bus IEEE Standard Test System to show effectiveness of the proposed method. The use of MATLAB programming shows the result of simulation of increasing power quality achieved for all scenario of proposed method.

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1. INTRODUCTION

The economic and technological improvement followed by increasing the use of electricity is a major challenge that carries complex problems especially in the case of power quality. The smarter distribution system is expected to drive the good power quality in the distribution system. Nowadays, non-linear load on control devices and power switching apparatus increase rapidly due to the high efficiency and easy operation and control [1]. The harmonic problems are mainly due to the substantial increase of non-linear load because of technological advances such as the use of power electronic circuit and devices and AC/DC transmission links or the control of power system using power electronics or microprocessor controllers. Increase in harmonic spread will result in additional heating losses, shorter insulation lifetime, higher temperature and insulation stress, reduced power factor, and error on measurement [2], [3]. Modern appliances are increasingly adopting power electronic devices faced nowadays due to energy efficiency considerations. This trend has generated the increased harmonic distortion in the power residential distribution system now that harmonic distortion by residential load has apparently become an increasing concern due to the extensive adoption of power electronic-based home appliances [4]. The harmonic source produces a non-sinusoidal current which flaws where each periodic wave is not a sinus form containing harmonic. Reviewing the consequences arising from the distribution of harmonics, harmonic load flow method is used to determine and analyze the spread and magnitude of harmonic in the distribution system [5]-[8]. Backward-forward method for a power flow analysis is applied to obtain a voltage profile on each

bus and the real power losses at fundamental frequencies, and harmonic load flow is practiced obtaining the distortion voltage profile on each bus and the harmonic losses caused by the use of non-linear loads [9]-[11].

The use and development of small-scale electric power plants integrated into radial distribution systems is a new breakthrough known as distributed generation (DG). The DG operation process is relatively simple, and DG is able to improve power quality and easily obtain environmentally friendly and primary energy sources [12], [13]. The placement of DG can comply with the harmonic limits discussed in [14]-[16]. Harmonic resonance problems have been minimized by the use of the smart DG in distribution systems [17]. The distorted current injected by the DG based renewable source can make a harmonic problem more severe if the placement of DGs is applied with the non-optimal size [18], [19]. The capacitors are reactive power compensators. However, the similar ones can magnify the effect of harmonics of the load due to the existence of resonance with the inductive elements. The effects of capacitor integration on voltage largely depend on their size and placement. However, they can increase or reduce the spread of harmonics in the distribution system [20], [21]. Distribution network reconfiguration is a technique that has been identified as an effectively helpful method for improving the performance of systems by minimizing active power losses, balancing load, improving service, and increasing the voltage profile on each bus in radial distribution systems [22]. Distribution system reconfiguration primarily proposed for the loss minimization has been recently considered an effective solution for many power quality problems in the grids. New reconfiguration solution strategies for the harmonic minimization are proposed [23]. Distributed energy resources (DERs) are some energy sources that can enhance the performance system and can be operated in on and off grid modes. DERs are usually connected at the distribution system due to their power and voltage range. DERs provide an additional opportunity for mitigation of harmonics spreads in distribution systems [24].

The spread of harmonics in distribution systems requires a special attention to the planning and design of distribution system expansion. Inadequate planning and operation can worsen the condition of the system and result in the damage to the equipment due to the spread of harmonics. An intelligent planning is able to maintain and improve the performance summarized in a coordinated planning. Coordinated planning is a planning activity that coordinates several optimization techniques to achieve the stated objective function. Several previous studies on the combination of optimization techniques overcome the spread of harmonics in the distribution system. A combination of network reconfiguration and DG placement uses the branch exchange technique method. Reconfiguration is less effective after DERs are placed, and the combination of optimization techniques had better be simultaneously carried out [22]. Evaluation of network reconfiguration for several types of loads uses the non-iterative harmonic load flow method by forward backward sweep. The reconfiguration result is influenced by the load model in the system tested by IEEE 69-bus standard test system. [25]. Capacitor placement and network reconfiguration done simultaneously using the New-PSO, ACO, and HS methods generate a better numerical result better than those done sequentially with multi objective functions such as minimum P_{Loss} and % THD_v [26]. Optimization of placement of DERs (DG and Capacitor) uses the BBO, PSO, ABC, and DE Method. Investigation of the uses of metaheuristic methods results in different performances tested in the IEEE 33-bus test standard system. The DG placement done with and without capacitors installed in the system significantly influences power quality on each used method. Power factor value consideration on the capacitors impacts the effect of harmonic distortion, and the simultaneous application of two optimization techniques is highly recommended [27] and teaching learning based optimization method needs applying to optimize the power injection of the DERs on the particular places in the distribution system considering nonlinear loads for the power quality improvement [28].

A smarter distribution system is expected to control good power quality to the system. However, this case is a complicated demand to maintain according to the needs and increase the existing load. Especially with the use of semiconductor equipment or the switching process which is increasing rapidly due to high efficiency and ease of operation and control [29]. Coordinated planning in the form of planning activities to coordinate optimization techniques from DG placement, capacitor placement and network reconfiguration on a radial distribution system to produce the best strategy in finding solutions to combinatory optimization problems that have a single or multiple objective function according to the constraints determined by sequentially or simultaneously [30]. The combination of three optimization techniques namely DG placement, Capacitor placement and network reconfiguration using the genetic algorithm method which is summarized in a coordinated plan to maximize optimal power flow that obtains a better result than two techniques [31], [32]. In order to obtain the best benefit regarding power quality considering the harmonic spread, the combination of three optimization techniques is implemented. A few studies have confirmed that the use of artificial intelligence (AI) methods is considered capable of the best solution. Particle swarm optimization (PSO) is one of the AI types considered being able to offer the best solution in solving issues on the optimization technique used [33]. This research will discuss the development of previous research related to the optimization of a combination of three optimization techniques that aim to improve power quality to the distribution of harmonics by considering the use of non-linear loads in a radial distribution system using

the particle swarm optimization method with a harmonic load flow method by forward backward sweep method.

2.   METHOD
2.1. Objective function
Objective function used to optimize the optimization technique performed in coordinated planning in this study is in the form of a multi objective function, i.e.

1)   Minimum active power losses (P_{Loss})

The fundamental active power losses component and the harmonic component are defined.

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

$$f(x)_1 = \min P_{Loss} \tag{2}$$

P_{Loss} = Total active power losses
$P_{Loss_i}^{(1)}$ = Fundamental active power losses
$P_{Loss_i}^{(h)}$ = Harmonic component active power losses
h_{max} = the maximum harmonic orders
h_0 = the minimum harmonic orders

2)   Minimum total harmonic distortion (THD)

THD of voltage is one of principal indexes of distortion considered by IEEE519-1992 Standard. Reducing THD enhances power quality standards and allows the finding of solution with lower distortion indexes.

$$\%V_{THD,i} = \frac{V_{d,i}}{V_{rms,i}} * 100\% \tag{3}$$

$$f(x)_2 = \min \%V_{THD_i} \tag{4}$$

$V_{THD,i}$ = total harmonic distortion voltage
$V_{d,i}$ = absolute voltage on fundamental frequency
$V_{rms,i}$ = total rms voltage

3)   Minimum voltage deviation (ΔV)

Voltage deviation is defined as a difference between the maximum (swing bus) and other voltage bus on each bus. By reducing voltage deviation, the optimization process can improve the voltage condition in all system nodes and for all the load level.

$$\Delta V = \left| \frac{V_i - V_1}{V_1} \right| \tag{5}$$

$$f(x)_3 = \min \Delta V \tag{6}$$

ΔV = Voltage deviation
V_1 = Swing bus voltage
V_i = Voltage bus on each bus

The next step is to calculate the objective function. So, the equation of the multi objective function is,

$$f(x) = af(x)_1 + bf(x)_2 + cf(x)_3 \tag{7}$$

where a, b, and c are penalty factors that determine the sizing of the priority scale and find the objective function based on statistical information on losses, total harmonic distortion, and voltage deviation.

2.2. Constrain

1) Bus voltage limit

V_{min} and V_{max} represent the lower and the upper limits of the voltage at each bus i.

$$V_{min}(0.95\ pu) \leq V_{rms_i} \leq V_{max}(1.05\ pu) \tag{8}$$

2) Total harmonic distortion limit

The THD on each bus of the system should not exceed its maximum permissible value according to IEEE 519-1992 standard.

$$THD_i(\%) \leq THD_{max} \tag{9}$$

3) Number and sizing of DG

The number of DGs to be placed is 4 and the size are.

$$0\ kW \leq P_{DG} \leq 200\ kW \text{ for IEEE 33-bus test system} \tag{10}$$

$$0\ kW \leq P_{DG} \leq 250\ kW \text{ for IEEE 69-bus test system} \tag{11}$$

P_{DG} = Active power injected by DG

4) Number and sizing of capacitor

The number of capacitors to be placed is 4 and the size are.

$$0\ kVar \leq Q_{Cap} \leq 50\ kVar \text{ for IEEE 33-bus test system} \tag{12}$$

$$0\ kVar \leq Q_{Cap} \leq 100\ kVar \text{ for IEEE 69-bus test system} \tag{13}$$

Q_{Cap} = Reactive power injected by capacitor

5) The new distribution network topology remains in a radial condition after activating tie switch and opening sectional switch.

2.3. Particle swarm optimization (PSO)

In PSO, each particle that is roaming through the D-dimensional problem hyperspace represents the potential solution for a specific problem. For each of I two vectors X_i is position vector and V_i is velocity vector. In addition, each particle i can memorise its personal best experience ever encountered, represented by personal best position vector P_i. The position attained by the best particle in the society is represented as P_g. Mathematically, at iteration $(t+1)$ of the searching process, the dth dimention of particle i's velocity, $V_{i,d}(t+1)$ and position $X_{i,d}(t+1)$ are updated as follows [34].

$$V_{id}(t+1) = V_{id}(t) + c_1 rand_1(P_{id}(t) - X_{id}(t)) + c_2 rand_2\left(P_{gd}(t) - X_{id}(t)\right) \tag{14}$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \tag{15}$$

V_{id} = Particle speed
c_1, c_2 = Coefficient of acceleration
$rand_1, rand_2$ = Random particle position
P_{id} = Local best position
X_{id} = Particle position
P_{gd} = Global best position

Parameter PSO used is the population=100, iteration=100, a=0.5, b=0.5, c=0.5, c_1=2 and c_2=2. The stages of the research carried out is shown in Figure 1. In this study, the sizing a, b, and c is made equivalent in finding multi objective function on the constrain determined.
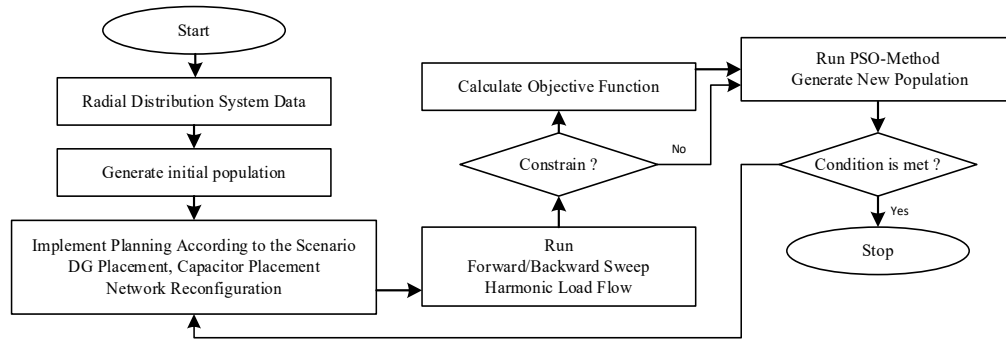
Figure 1. Flowchart of research stages

2.4. Object data and study case
2.4.1. Harmonic source

The harmonic sources from nonlinear load will be given to load bus which aims to generate the distribution of harmonics in radial distribution system which is shown in Table 1.

Table 1. Injection of harmonic source in load bus [35]

Orde	Magnitude (%)	Angle
5	98	140
7	39.86	113
11	18.85	-158
13	9.79	-178
17	2.5	-94

2.4.2. IEEE 33-bus

In IEEE 33-bus radial distribution system, the main feeder originates from the substation and passes through different costumer load. There are 32 sectional switches and 5 tie switches that is shown in Figure 2. Harmonic source will be injected on bus 5, 7, 9, 11, 14, 17, 20, 24, 27, 29, 31 and 33. The total peak demand of system is 4.37 MVA, and power factor is 0.85. All data on this system is in per-unit (pu) form where the best values of power and voltage are 100 MVA and 12.66 kV.
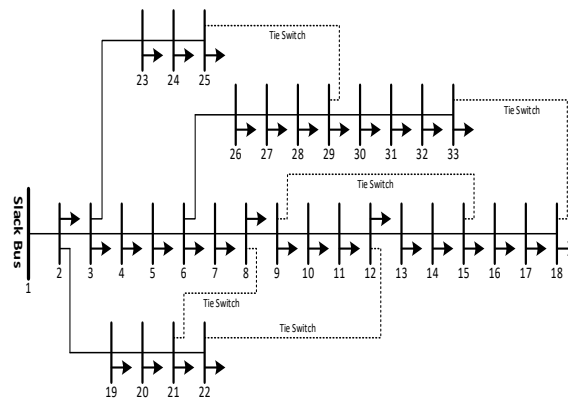

Figure 2. IEEE-33 bus test system

2.4.3. IEEE 69-bus

On IEEE-69 bus, there are 47 sectional switches and 5 tie switches that is shown in Figure 3. Harmonic source will be injected on bus 6, 9, 14, 17, 22, 27, 33, 37, 40, 43, 49, 55, 61, and 69. On the IEEE 69-bus test system, the total peak demand of system is 4.66 MVA, and the power factor is 0.81. All data on this system are in per-unit (pu) form where the best values of power and voltage are 100 MVA and 12.66 kV.
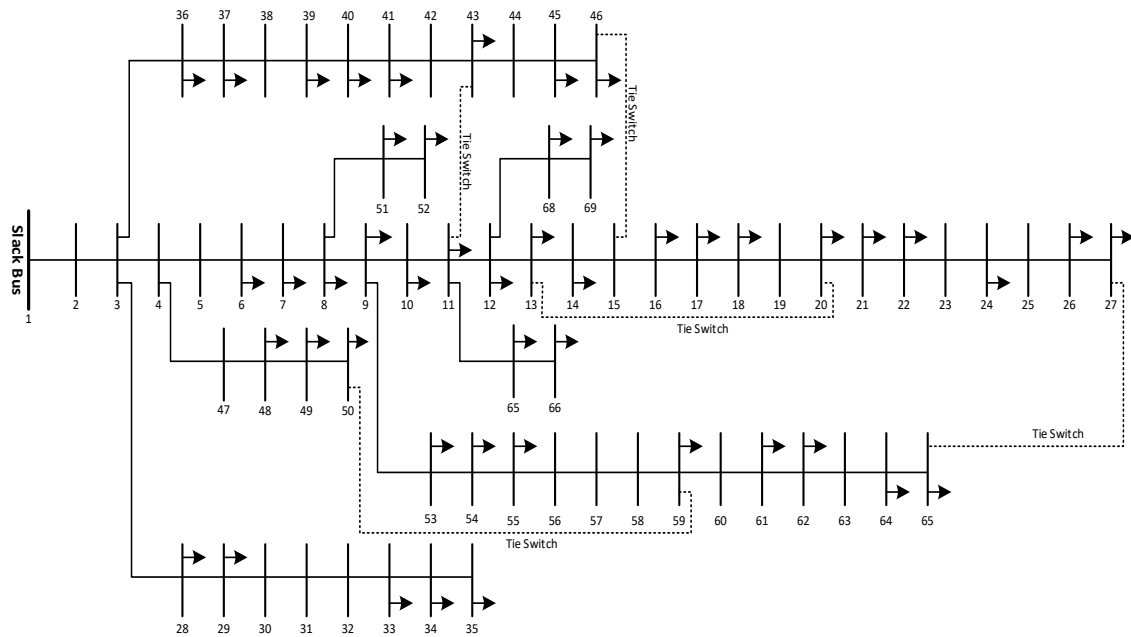
Figure 3. IEEE-69 bus test system

2.4.4. Study case

This research conducted a simulation of several study cases to determine the effect of optimization techniques on coordinated planning in finding the objective function. To test the effectiveness of the optimization technique proposed in this study, a simulation of combination of optimization techniques that has been proposed by previous studies is carried out using the PSO method.

1. Scenario 1 (S-1). Normal case
2. Scenario 2 (S-2). Network reconfiguration
3. Scenario 3 (S-3). DG placement
4. Scenario 4 (S-4). Capacitor Placement
5. Scenario 5 (S-5). DG placement and capacitor placement
6. Scenario 6 (S-6). DG placement and network reconfiguration
7. Scenario 7 (S-7). Capacitor placement and network reconfiguration
8. Scenario 8 (S-8). DG placement, capacitor placement and network reconfiguration

3.   RESULTS AND DISCUSSION

Harmonic current injection on load bus by placing harmonic source will generate harmonics spread on the system. The searching results of the optimization techniques carried out in coordinated planning based on a predetermined scenario use the particle swarm optimization method.

3.1. IEEE 33-bus test system

The result of the optimization technique performed is shown in Table 2, Figure 4, Figure 5, and Figure 6. Table 2 shows the simulation results for all scenarios for the IEEE 33-bus test system. The use of PSO Algorithm is able to provide the best solution for the planning carried out. Simulation results for all scenarios vary based on the ability of the optimization techniques used in finding desired solutions that are seen by decreasing the value of fitness. Scenario 8 provides the best solution in this plan that can reduce total active power losses by 67.89% or 82.85 kW both in terms of fundamental and each order of harmonic distortion.

Reviewing the spread of harmonic distortion also improved with a decrease in the THDv value (%) on each bus that does not pass IEEE Standard 519-1992 as shown in Figure 4. Each scenario has its own performance in reducing the spread of harmonic distortion to the use or combination of optimization techniques used. Figure 5 shows that all the techniques used are able to improve the voltage profile better than the baseline condition (Scenario 1) without exceeding the allowable limit so that the voltage deviation value in each load bus decreases as shown in Figure 6.

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Table 2. Result of study case IEEE 33-bus test system

| Parameter		S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8
Fitness		-	38.722	41.508	66.208	38,193	37.670	40.219	25.456
DG (kW)	Loc	-	-	7, 9, 17, 31	-	13, 17, 29, 31	9, 12, 10, 20	-	7, 16, 29, 31,
	Sizing	-	-	200, 200, 200,200	-	200, 200, 200, 200	200, 200, 70.21, 200	-	200, 200, 200, 200
Cap (kVar)	Loc	-	-	-	8, 15, 17, 26	3, 17, 25, 29	-	6, 7, 14, 32	5, 8, 31, 33
	Sizing	-	-	-	50, 50, 50, 50	50, 50, 50, 50	-	50, 50, 50, 50	50, 50, 50, 50
Active Tie		-	8-21	-	-	-	12-22	12-22	8-21
Sec Tie Open		-	6-7	-	-	-	10-11	8-9	7-8
P_{Loss} (kW)		122.03	64.16	68.75	114.81	63.08	65.43	71.60	39.18
Q_{Loss} (kVAr)		87.86	55.19	38.63	82.7	35.54	46.99	50.77	27.39
THD max		5.116	3.368	2.568	4..793	2.161	3.363	3.632	2.636
THD min		0.456	0.300	0.272	0.451	0.295	0.011	0.007	0.197
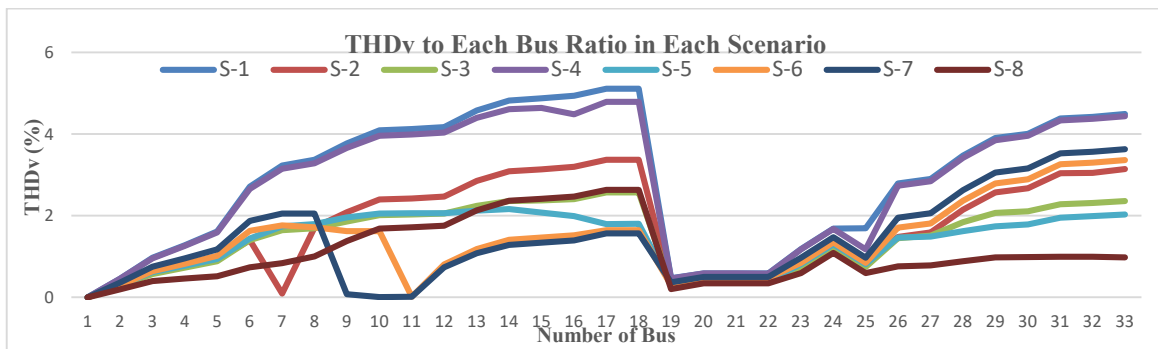
Figure 4. THDv value on each bus for all scenarios for IEEE 33-bus test system
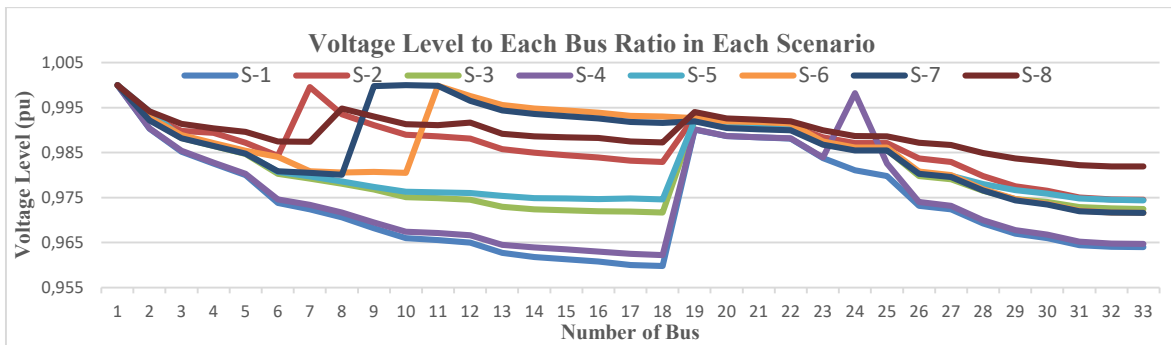

Figure 5. Level of voltage bus on each bus for all scenario for IEEE 33-bus test system
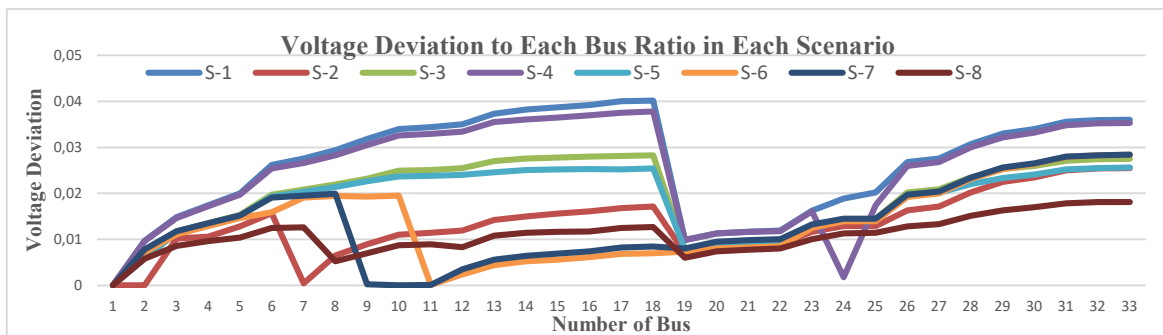

Figure 6. Voltage deviation value on each bus for all scenario for IEEE 33-bus test system

The use of optimization techniques that are single from the three optimization techniques that provide the best solution is reconfiguration network (S-2). Network reconfiguration is able to change the value of network impedance that can change the electric current flowing and repair voltage levels followed by reduced active power losses. The magnitude of the spread of Harmonic distortion in the system is very dependent on the current flowing on the load and the voltage level on each bus so that the spread of harmonic distortion can be reduced by network reconfiguration techniques as in research [22], [36], [37]. The size of DG placement and capacitor placement resulting in the use of the PSO algorithm are at the maximum limit. Thus, the performance of the system will be better in improving the quality of power with a size of DG >200 kWatt and capacitors >50 kVAr. The combination of three optimization techniques can simultaneously provide the best performance to improve power quality in reducing the spread of harmonic distortion.

3.2. IEEE 69-bus test system

The result of the optimization technique performed is shown in Table 3, Figure 7, Figure 8, and Figure 9. Table 3 shows the simulation results for all scenarios for the IEEE 69-bus test system. In contrast to the IEEE 33-bus test system, with almost the same total load, the IEEE 69-bus test system has a larger number of load buses so that the network impedance is greater that makes the spread of harmonic distortion in the form of THDv exceed the allowable limit of up to 7.673% on bus 65. In addition, the reactive power losses value in the 5th order is 128.41 kVar, which is greater than its fundamental value. The use of the PSO method from all existing scenarios can increase power quality where there is a decrease in active power losses by 39.62% or 107.01 kWatt in scenario 8 and 37.54% or 101.39 kWatt in scenario 2.

Table 3. Result of study case IEEE 69-bus test system

| Parameter		S.1	S.2	S.3	S.4	S.5	S.6	S.7	S.8
Fitness		-	77.5693	99.6067	113.6014	93,2101	79.3485	83.6948	76.1402
DG (kW)	Loc	-	-	23, 51, 61, 63	-	27, 36, 59, 65	2, 20, 24, 45	-	10, 11, 37, 56
	Sizing	-	-	231, 193, 241, 214	-	192, 95, 219, 232	163, 157, 190, 122	-	29, 120, 170, 87
Cap (kVar)	Loc	-	-	-	14, 17, 21, 27	9, 32, 36, 65	-	5, 43, 50, 66	29, 47, 60, 69
	Sizing	-	-	-	65, 62, 93, 77	47, 26, 87, 81	-	60, 25, 76, 38	6, 71, 6, 91
Active Tie		-	50-59	-	-	-	11-43	11-43	50-59
Sec Tie Open		-	58-59	-	-	-	8-9	8-9	55-56
P_{Loss} (kW)		270.05	168.66	208.30	255.16	214.59	192.32	202.46	163.04
Q_{Loss} (kVAr)		248.32	258.26	199.41	235.79	212.59	177.75	180.85	251.21
THD max		7.673	7.663	6.827	7.561	7.384	6.414	6.372	7.539
THD min		0.006	0.006	0.005	0.006	0.005	0.001	0.001	0.005
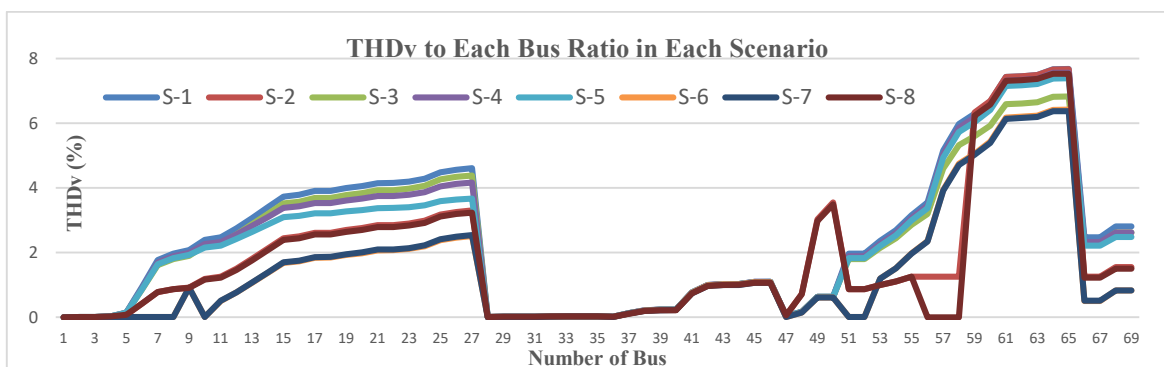
Figure 7. THDv value on each bus for all scenarios for IEEE 69-bus test system

The reduction in the spread of harmonic distortion occurs in every scenario that is shown in Figure 7 but still exceeds the allowed limit. The improvement of the voltage level on each bus and the reduced voltage deviation that is shown in Figure 8 and Figure 9. The use of optimization techniques, both single and plural, has been said to improve the performance of the system in terms of improving the quality of power against the spread of harmonic distortion but not yet maximized.
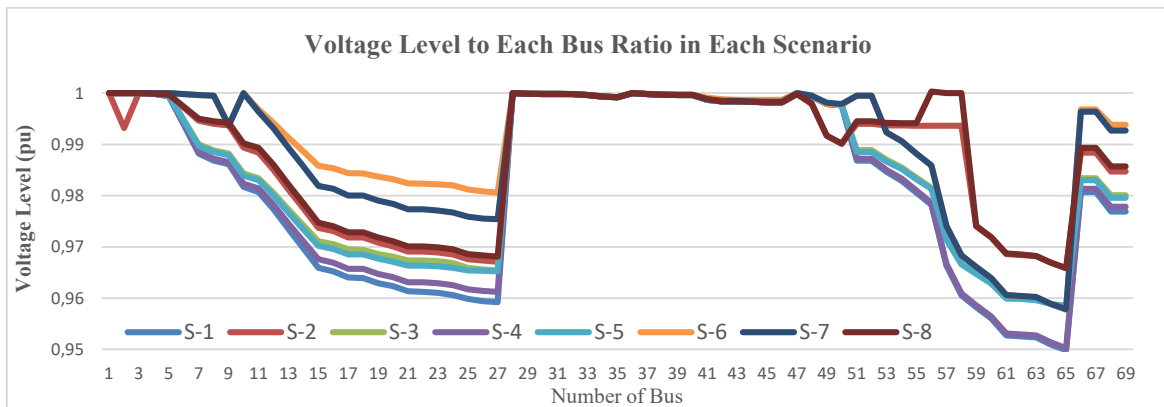
Figure 8. Level of voltage bus on each bus for all scenario for IEEE 69-bus test system
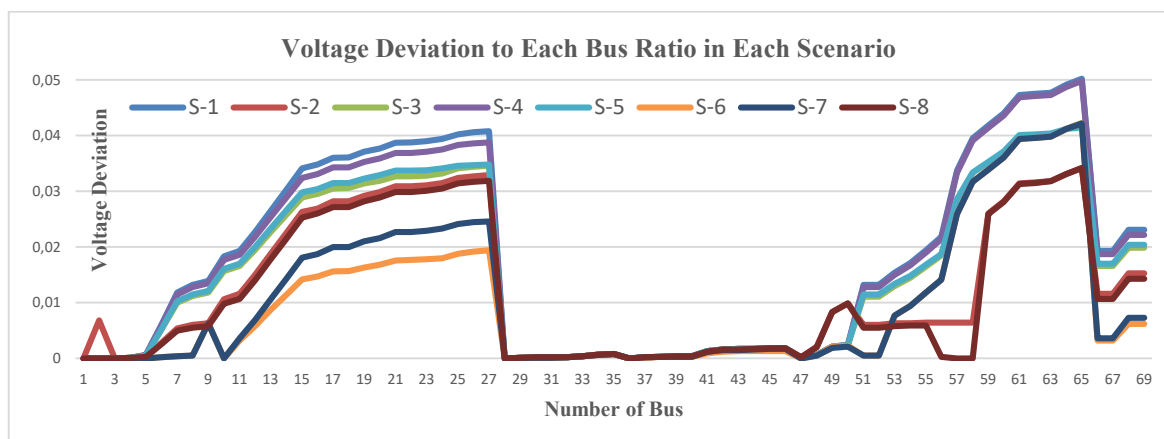

Figure 9. Voltage deviation value on each bus for all scenario for IEEE 69-bus test system

4.   CONCLUSION

In this paper, the use of the PSO algorithm is able to provide solutions to all scenarios carried out in finding the objective function in increasing power quality to the spread of harmonics. The simulation results verify that the effectiveness of the proposed method and also the solution to all scenarios carried out. Planning that gives maximum result is in scenario 8 in the form of a combination of three simultaneous optimization techniques between DG placement, capacitor placement and network reconfiguration of the two objects used. Taking into account harmonic distortion resulting from the use of non-linear loads in the radial distribution system as a multi-objective function provides the appropriate criteria in carrying out this planning. Further planning is needed regarding the handling of harmonics distribution in a larger distribution system and real distribution systems in Indonesia which will be discussed in the next paper with other method.

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