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Article

Assessment of Voltage Imbalance Improvement and Power Loss Reduction in Residential Distribution Systems in Taiwan

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Abstract: In this study, the non-dominated sorting genetic algorithm II (NSGA-II) is used to optimize the annual phase arrangement of distribution transformers connected to primary feeders to improve three-phase imbalance and reduce power loss. Based on the data of advanced metering infrastructure (AMI), a quasi-real-time ZIP load model and typical sample distribution systems in Taiwan are constructed. The equivalent circuit models and solution algorithms for typical distribution systems in Taiwan are built using the commercial software package MATLAB. A series of simulations, analyses, comparisons, and explorations is executed. Finally, the quantitative evaluation results for improving the voltage imbalance and reducing the power loss are summarized. For the series of studies, the percentage reductions in (1) total power imbalance TS_I, (2) total line loss TL_L, (3) average voltage drop AV_D, (4) total voltage imbalance factors for zero/negative sequences Td_0/Td_2, and (5) neutral current of the main transformer I_{LCO} are up to 45.48%, 4.06%, 16.61%, 63.99%, 21.33%, and 88.01%, respectively. The results obtained in this study can be applied for energy saving and can aid the authorities to implement sustainable development policies in Taiwan.

Keywords: conservation voltage regulation; distribution system; non-dominated sorting genetic algorithm; voltage imbalance

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1. Introduction

1.1. Background

The worldwide energy demand is continuously increasing. Meeting this demand requires careful work from all parts of power generation, power distribution, and user integration. However, many problems still persist in distribution systems, such as energy loss and voltage imbalance [1], where the complexity of loading conditions is among the many causative factors. In Taiwan, the complexity of the load behavior is also a problem. Taiwan Power Company (Taipower), a state-owned electric power industry, has adopted three-phase three-wire (3Φ3w) and single-phase three-wire (1Φ3w) in its power distribution systems to service three-phase and single-phase loads, respectively. Since the loads are simultaneous, currently, three-phase four-wire (3Φ4w) is preferably deployed. However, it may pose a new problem of three-phase current and voltage imbalance in some feeders.

The system operating conditions are regarded as time-based load behaviors that vary. The optimal phase arrangement of distribution transformers can be used to solve the imbalance problem. Although it can improve voltage and current imbalances and reduce power loss in a practical setting, an extended evaluation is needed.

1.2. Literature Review

Energy efficiency and saving are the main concerns in distribution systems because power losses caused by voltage imbalance occur unpredictably. Hence, many researchers and engineers have focused on conservation voltage regulation (CVR). In accordance with

Article 36 of the Taiwan Electricity Act, the CVR is an energy-saving measure [2] that can reduce electricity system demands [3].

The CVR has been extensively explored [4] to mitigate power consumption and peak load demands. A three-phase AC optimal power flow-based CVR was conducted to minimize the energy consumption in medium-low voltage networks [5]. Unbalanced UK residential networks were also assessed. With 50% photovoltaic (PV) penetration, the results show that energy import minimization is achieved, enabling the regulation of medium-low voltage networks. A Pareto particle swarm optimization (PPSO) was proposed in a previous study [6] for a trade-off analysis in a low-medium-voltage UK residential. However, Gutierrez-Lagos et al. [5] only developed CVR based on three-phase optimization, while Gharaviahangar et al. [6] focused on one-minute time resolution with four different scenarios of CVR operation.

A time-dependent CVR investigation with a smart grid solar PV inverter was also conducted to obtain higher energy savings in distribution systems [7]. Using three schemes, including without CVR, only CVR, and CVR with PV, this study shows that the last scheme outperforms other schemes in reducing peak load demand and saving energy. A voltage control algorithm for home energy management (HEM) was proposed in [8]. The load power threshold was used to control the voltage reduction in Turkey. This study achieved a remarkable peak demand reduction of 17.5% with voltage control and 38% with voltage control and appliance shifting.

Energy-saving and load peak demand via CVR were also explored by Singh et al. [9]. Three scenarios, including CVR, volt-ampere reactive (VAR) optimization (VVO)-based CVR, and CVR with community energy storage (CES), were investigated. However, this work might only consider the problem in a specific period (hourly and peak loads).

Davye Mak et al. investigated CVR using mixed-integer linear programming [10], resulting in remarkable energy savings. PV, energy storage system (EES), and demand response were integrated into their study. Although the results were promising, this study focused on the hourly schedule of the CVR performance investigation. By using penalty successive linear programming (PSLP), excellent CVR results can be obtained via coordinated voltage control and a local control approach [11]. However, this implementation is difficult to achieve in a practical setting.

Moreover, the genetic algorithm (GA) appears to be an assuring method for solving CVR problems. A GA with autonomous and aggregated smart inverter controls was utilized in the study by Ding et al. [12]. This study reported a promising performance with approximately 1.8–3.6% and 0.3–0.9% energy-saving addition for legacy voltage regulating devices and smart inverter addition, respectively. The time-varying CVR for five different scenarios was investigated monthly.

Recent studies have revealed that residential-scale power consumption accounts for 40% of the energy consumption [13,14]. In broader effects, dealing with voltage imbalance may contribute to better livelihoods and public economic development [15]. In general, the operating voltages are restricted within 95–105% of the nominal voltage for hybrid loads. In practice, voltage regulators operate as three-phase interlocks. Therefore, a three-phase imbalance may affect the service range of voltage regulation, that is, the voltage imbalance may have a significant effect on the performance of the CVR strategy. Before performing the CVR strategy, the three-phase imbalance is first improved. Once the phase arrangement of the distribution transformers changes, service continuity is interrupted unavoidably. The phase arrangement of distribution transformers cannot be implemented frequently. However, the phase arrangement of distribution transformers connected to primary feeders is a complicated multi-objective engineering problem with multiple constraints. The conventional trial-and-error method cannot be used to find the optimal solutions for the phase arrangement of the distribution transformers. Most of the existing research works treat the optimal phase arrangement of distribution transformers as a single-objective optimization problem using the weight sum method [16–18]. The weight sum method may cause imbalanced effects among objective functions. However, most of the aforementioned studies were heavily dependent on the specific time. Therefore, the non-dominated sorting genetic algorithm (NSGA-II) has been widely adopted [19–21] due to its flexibility and efficiency. There have been several successful applications of NSGA-II in recent years. For example, in one study [22], NSGA-II was associated with a discrete event simulation for safety system design and multi-objective maintenance problems. The simulation was performed using different encoding methods, and the results showed various accuracies. In [23], NSGA-II was employed with the adaptive neuro-fuzzy interference system (ANFIS) to solve the optimization problems of short-term electric power demand forecasting because of its superior forecasting accuracy. Moreover, NSGA-II was implemented in [24] to analyze the energy consumption of a deep-sea self-sustaining profile buoy (DSPB). The results show that NSGA-II can lead to good performance accuracy and timeliness. In addition, a comparative study of multi-objective optimization (MOO) was investigated by Li et al. [25]. The performances of MOOs, such as multi-objective particle swarm optimization (MOPSO), multi-objective genetic algorithm (MOGA), and multi-objective differential evolution (MODE), are compared with NSGA-II. NSGA-II is one of the most commonly used MOOs. The results show that NSGA-II has a better average performance than the others. Moreover, NSGA-II also shows good performance in terms of computational time. Gao et al. [26] used an improved NSGA-II algorithm to predict the load power of a hybrid ship under load uncertainty. The results indicate that the improved NSGA-II can solve the optimization problems with a high running speed and good convergence of the solution set. In another study [27], NSGA-II was selected to optimize the rotor tooth profile of a gerotor pump. The results demonstrate that NSGA-II provides a good solution convergence set at a high computational running speed. Furthermore, Xu et al. [28] used NSGA-II to calculate the performance and optimize the configuration of the annular radiator using heat transfer unit simulation. This NSGA-II application indicates that penalty functions and Lagrange multipliers are not necessary in this method, and they offer faster computational times than the traditional Pareto ranking method.

1.3. Aim and Contribution

In our previous work [16], a GA-based approach was proposed to optimize the phase arrangement of distribution transformers connected to a primary feeder to improve the three-phase imbalance and reduce power loss. However, the optimal phase arrangement between the distribution transformers and feeder is available for a specific time. Based on the above explanation, the contributions of this study are as follows:

(1) An annual phase arrangement of distribution transformers connected to primary feeders for improving the three-phase imbalance and reducing power loss is proposed using NSGA-II.
(2) The five objective functions used in this study are (1) total power imbalance, (2) total line loss, (3) average voltage drop, (4) total voltage imbalance factor, and (5) neutral current of the main transformer.
(3) Seven typical distribution systems in Taipower were examined for potential CVR solutions on residential dwellings in Taiwan.

1.4. Paper Organization

This study is divided into five sections. Section 1 is the introduction, including the background, aim, and contributions. Section 2 explains the multi-objective optimization problems. In Section 3, NSGA-II is presented to improve the voltage imbalance and reduce power loss in residential distribution systems in Taiwan. In Section 4, a problem formulation with objectives and constraints is proposed. The results and discussion are presented in Section 5. Finally, Section 6 concludes the paper.

2. Multi-Objective Optimization Problems

A multi-objective optimization problem can be defined as,

$$\min/\max y = (f_1(x), f_2(x), \cdots, f_k(x)), \tag{1}$$

subject to,

$$x = (x_1, x_2, \cdots, x_n) \in X, \tag{2}$$

$$y = (y_1, y_2, \cdots, y_k) \in Y, \tag{3}$$

$$g_j(x_n) = b_j. \tag{4}$$

In practical problems, a clash between the objectives always occurs. Usually, it is difficult to optimize the parameters for all objectives simultaneously. Hence, Pareto optimality was used to address these problems. Pareto-optimal solutions are non-dominated solutions. All non-dominated solutions are merged to form the Pareto-optimal set. The Pareto front is defined as the set of objective vectors of the Pareto-optimal set, as shown in Figure 1. If the following conditions are satisfied, a solution $\boldsymbol{x}$ dominates $\boldsymbol{y}$ ($x \prec y$), as explained below:

$$\forall_i \in \{1, 2, \cdots, k\} : f_i(x) \leq f_i(y) \quad \bigwedge \quad \exists_j \in \{1, 2, \cdots, k\} : f_j(x) < f_j(y). \tag{5}$$

A vector x^* is a Pareto-optimal solution if $f(x^*)$ is non-dominated by any $f(x)$ for every $\boldsymbol{x}$.

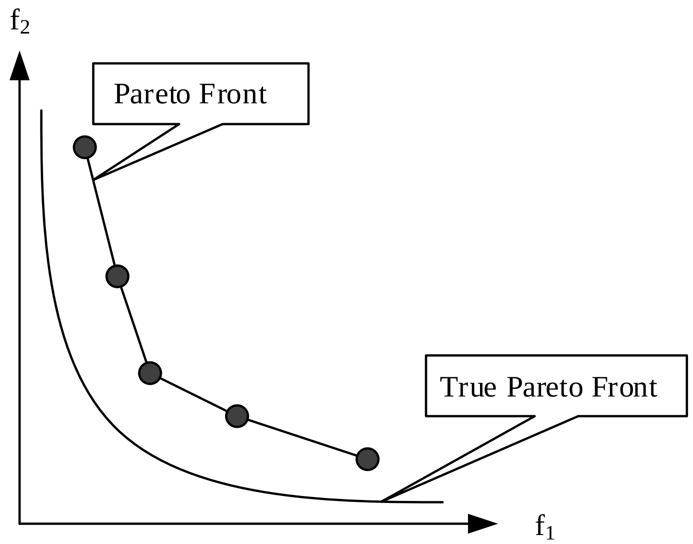

Figure 1. True Pareto front and Pareto front.

3. Non-Dominated Sorting Genetic Algorithm II

A single-objective GA-based method is modified to non-dominated solutions during each iteration as a population-based method. The GA has the ability to search for different solutions in the solution space with multiple boundaries for solving non-convex, discontinuous, and multimodal problems. The mating procedure in the GA is expected to search for unexplored non-dominated solutions in the objective space. In general, two types of optimization methods are used to find a single solution for a multi-objective problem. In the first type of method, a priori preference information and single-objective optimization techniques are used. A multi-objective problem is a combination of these problems. For classical multi-objective optimization methods, one combines multi-objective functions that are transformed into a single objective function. The other method is to solve the Pareto optimal solution set. The Pareto optimal solution is a set of nondominated solutions. For real-world problems, the Pareto optimal solution is better than a weight-sum single-function solution. Decision makers can make choices based on the current situation.

Most multi-objective optimization algorithms focus on searching the Pareto front approaching the true Pareto front, as shown in Figure 2. In previous studies [19,20], NSGA-II required only a single parameter with easy modification and less computational complexity. The solutions can effectively approximate the true Pareto front.

3.1. Fast Non-Dominated Sorting Approach

The fast non-dominated sorting approach is a type of Pareto sorting method. In the Pareto sorting method, Pareto dominance is used to evaluate the fitness of each solution. The fast non-dominated sorting approach can be divided into two steps.

1. Determination of dominance: Using (5), the dominance of all solutions can be determined. n_p is the number of solutions that dominate solution $\boldsymbol{p}$. S_p represents a set of solutions dominated by solution $\boldsymbol{p}$. If solution $\boldsymbol{p}$ dominates solution $\boldsymbol{q}$, then solution $\boldsymbol{q}$ is added to the S_p. Otherwise, $n_p = n_p + 1$. After the sorting procedure, the solutions with $n_p = 0$ belong to the first non-dominated front (F_1), as shown in Figure 2.
2. Sort of the non-dominated fronts: For each solution $\boldsymbol{p}$ with $n_p = 0$, each member $\boldsymbol{q}$ of S_p is searched, and $n_q = n_q - 1$. If any member $\boldsymbol{q}$ with $n_q = 0$, these members belong to the second non-dominated front (F_2). The process continues until all the fronts are identified.

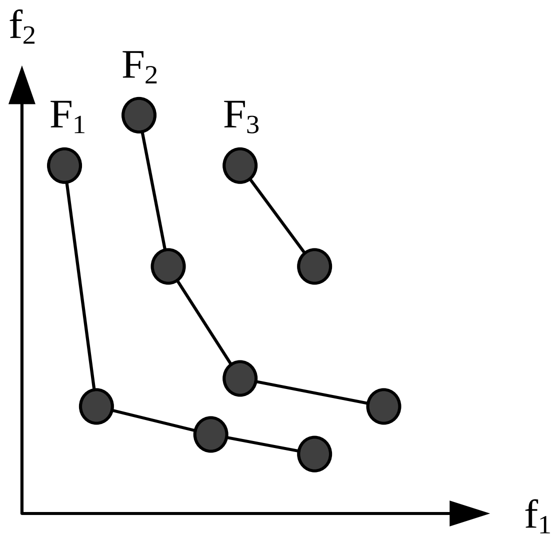

Figure 2. Fast non-dominated sorting approach.

3.2. Diversity-Preserving Approach

Maintaining the diversity of solutions is an important consideration in multi-objective GA. In NSGA-II, crowding distance is used to maintain diversity in a population. All non-dominated solutions can be spread uniformly in the objective space.

In the crowding distance assignment, the population is sorted according to each objective function value in ascending order. In (6) and (7), the boundary solutions with the maximum and minimum objective function values are regarded as an infinite distance. The absolute normalized difference in the objective function values of two adjacent solutions is regarded as the distance (see Figure 3). The crowding distance is the sum of the individual distances, as shown in (7) below:

$$cd_k\left(x_{[i,k]}\right) = \frac{f_k\left(x_{[i+1,k]}\right) - f_k\left(x_{[i-1,k]}\right)}{f_k^{\max} - f_k^{\min}}, \tag{6}$$

$$cd(x) = \sum_k cd_k(x). \tag{7}$$

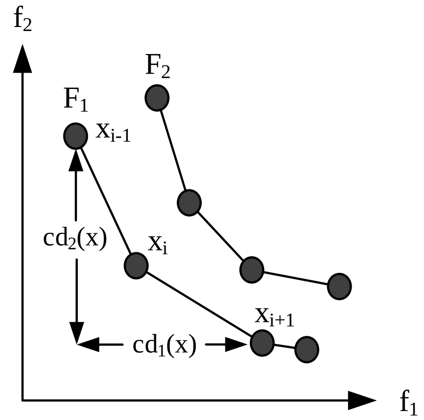

Figure 3. Diversity-preserving approach.

3.3. Elitist-Preserving Approach

In single-objective optimization, the elitism strategy means that the best solution will be able to survive in the next generation. However, non-dominated solutions are elite in the population. In NSGA-II, the combined population R_t is formed by P_t and Q_t. The parent population P_t at the t-th generation is used to create a new population Q_t via selection, crossover, and mutation. After non-dominated sorting, the non-dominated front $(F_1, F_2, \cdots, F_r)$ is determined. In the elitist-preserving approach, all members of set F_1 are selected for the new population P_{t+1}. The remaining members of the population P_{t+1} are selected from the remaining non-dominated fronts according to their ranking. If $|F_1 \cup F_2 \cdots F_r \cup F_{r+1}| > N$, all members of $F_1, F_2, \cdots, F_r$ are chosen for the population P_{t+1}. Then, the first $(N - |P_{t+1}|)$ members of the set F_{r+1} are chosen for the population P_{t+1}.

3.4. Constraint Handling Approach

In practice, multi-objective problems are accompanied by multiple constraints. The constraint-handling approach is used for tournament selection. If solution x constrained dominates solution y, if any of the following conditions are satisfied:

Condition 1: Solution x is feasible and solution y is not.
Condition 2: Solutions x and y are both infeasible, but solution x has a smaller constraint violation.
Condition 3: Solution x and y are feasible and solution x dominates solution y.

Any feasible solution has a better non-dominated rank than any infeasible solution. Regardless of the objective function values, the infeasible solutions can be eliminated.

3.5. Minimum Manhattan Distance

The Manhattan distance (also known as city block distance) between two points in an n-dimensional space is the sum of the absolute distances in each dimension. The solution that minimizes the distance from the normalized ideal vector is the minimum Manhattan distance. After normalization, the ideal vector y_{opt} is denoted as,

$$y_{opt} = \begin{bmatrix} \frac{\ell_1}{L_1} & \frac{\ell_2}{L_2} & \cdots & \frac{\ell_n}{L_n} \end{bmatrix}^t, \tag{8}$$

where $\ell_n = \min_{x \in N} y_n(x)$, $N = \{x_1, x_2, \cdots, x_M\}$, and $L_n = \max_{x \in N} y_n(x) - \min_{x \in N} y_n(x)$.

In the non-dominated solution set, the minimum distance sum between the ideal vector y_{opt} and the selected solution is defined as the minimum Manhattan distance, which can be calculated using,

$$\min_{x \in N} ||y_n(x) - y_{opt}|| = \min_{x \in N} \sum_{n=1}^{M} ||\frac{y_n(x)}{L_n} - \frac{\ell_n}{L_n}||. \tag{9}$$

A flowchart of the proposed NSGA-II-based approach is presented in Figure 4.

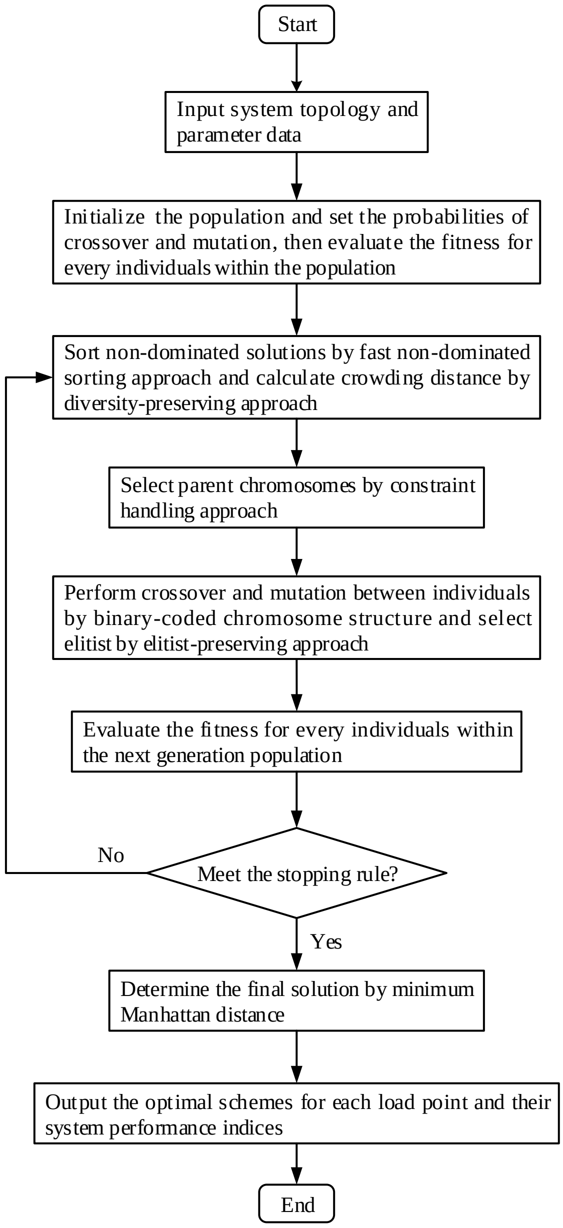

Figure 4. Flowchart of the proposed NSGA-II based approach.

4. Problem Formulation

4.1. Genes and Chromosomes

In this study, the control variables (discrete variables) in the NSGA II-based approach are the connection scheme of a distribution transformer tapped off a feeder. A binary-coded chromosome structure was formed, as shown in Figure 5. Six possible connection schemes were mapped to the six genes. Therefore, the length of the chromosome is the total number of distribution transformers in the target distribution system.

For three-phase loads, six possible connection schemes were adopted, as shown in Figure 6. However, the individual loads in three-phase loads may be different because the loads at the secondary side of the distribution transformer may consist of three-phase loads, double-phase loads (phase-phase loads), and single-phase loads (phase-neutral loads), as shown in Figure 7. The possible connection schemes for various types of load points are listed in Table 1.

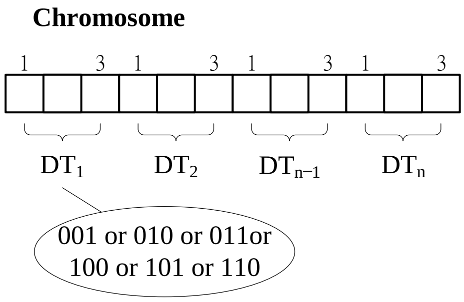

Figure 5. Chromosome structure.

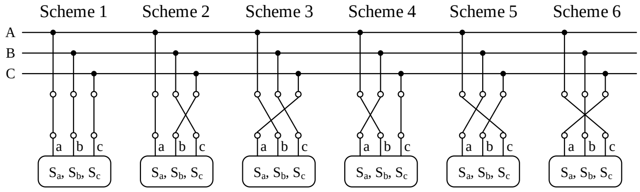

Figure 6. Six possible connection schemes for three-phase loads.

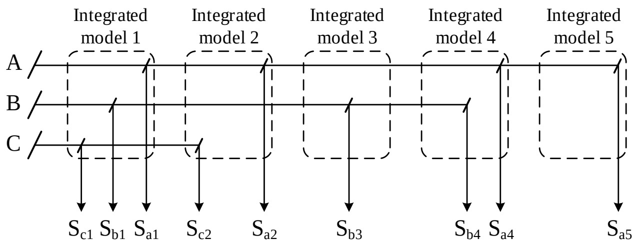

Figure 7. Integrated models of the sample feeder.

Table 1. Possible connection schemes for various types of load points.

Types of Load Points	Types of Integrated Models	Connection Schemes
ABC (3Φ)	abc, ab, bc, ca, a, b, or c	1–6
AB	ab, a, or b	1 or 4
BC	bc, b, or c	1 or 2
CA	ca, c, or a	1 or 6
A, B, C (1Φ)	a, b, or c	1

4.2. Objective Function

The five objective functions used in this study are (1) total power imbalance, (2) total line loss, (3) average voltage drop, (4) total voltage imbalance factor, and (5) neutral current of the main transformer.

4.2.1. Total Complex Power Imbalance

The imbalance of the three powers is an important indicator for evaluating the balance of power systems. The imbalance between the three powers can be evaluated as follows:

$$S_{t,j} = \sqrt{\frac{1}{3}\sum_{p=a}^{c}\left|\overline{S}_{t,j}^{p} - \overline{S}_{t,j}^{3\varnothing}\right|^{2}}, \tag{10}$$

$$\overline{S}_{t,j}^{3\varnothing} = \left(\overline{S}_{t,j}^{a} + \overline{S}_{t,j}^{b} + \overline{S}_{t,j}^{c}\right)/3, \tag{11}$$

where j is the j-th feeder segment, t is the t-th time interval, $\overline{S}_{t,j}^{3\varnothing}$ is the average of the three-phase power, $\overline{S}_{t,j}^{p}$ is the power in the j-th feeder segment, $p \in \alpha_p$, and $\alpha_p = \{a, b, c\}$.

If $S_{t,j} = 0$, the powers in the jth feeder segment are balanced. The total power imbalance in a feeder at time t is evaluated by:

$$TS_t = \sum_{j=1}^{m} S_{t,j}, \tag{12}$$

where m is the total number of feeder segments in a feeder.

The total power imbalance in a feeder during a designated period can be evaluated by,

$$TS_I = \sum_{I=1}^{T} \sum_{j=1}^{m} S_{I,j}. \tag{13}$$

when time T is selected to be in days, weeks, months, or years, it should be used in 96, 672, 2880, or 35,040 time intervals, respectively.

4.2.2. Total Line Loss

From the perspective of power utility, decreasing the power loss of power systems is a vital issue. Therefore, minimizing the total line losses is regarded as an objective function, as follows:

$$TL_L = \sum_{L=1}^{T} \sum_{j=1}^{m} \sum_{p=a}^{c} \left(I_j^p\right)^2 \cdot r_j^p, \tag{14}$$

where r_j^p is the resistance of the j-th line segment at the p phase, and I_j^p is the current in the jth line segment at the p phase.

4.2.3. Average Voltage Drop

Generally, the greater the load balance, the lower the voltage drops in the feeders. To improve the efficiency of CVR, reducing voltage drops and improving voltage differences among the three phases are important objectives. The voltage drop at the t time interval is evaluated by,

$$VD_{t,k} = \frac{1}{3} \sum_{p=a}^{c} \left| \frac{V_{rated} - V_{t,k}^p}{V_{rated}} \right| \times 100\%. \tag{15}$$

The average voltage drop is evaluated by,

$$AD_D = \frac{1}{n \cdot T} \sum_{t=1}^{T} \sum_{k=1}^{n} VD_{t,k}, \tag{16}$$

where n is the total number of load points on the feeder of interest, k is the load point k, t is the t-th time interval, V_{rated} is the rated phase voltage, and $V_{t,k}^p$ is the magnitude of the p-phase voltage.

4.2.4. Total Voltage Imbalance Factor

The total voltage imbalance factors for zero and negative sequences, labelled Td_0 and Td_2 are defined as follows:

$$Td_0 = \sqrt{\frac{1}{n \cdot T} \sum_{t=1}^{T} \sum_{k=1}^{n} \left(\frac{V_{t,k}^{(0)}}{V_{t,k}^{(1)}} \right)^2}, \tag{17}$$

$$Td_2 = \sqrt{\frac{1}{n \cdot T} \sum_{t=1}^{T} \sum_{k=1}^{n} \left(\frac{V_{t,k}^{(2)}}{V_{t,k}^{(1)}} \right)^2}. \tag{18}$$

where k is the load point k, t is the t-th time interval, $V_{t,k}^{(0)}$ is the zero-sequence voltage, $V_{t,k}^{(1)}$ is the positive-sequence voltage, and $V_{t,k}^{(2)}$ is the negative-sequence voltage.

4.2.5. Neutral Current of Main Transformer

To avoid malfunction of the zero-sequence relay, the neutral current in a wye-connection transformer is restricted to a specified threshold. The neutral current is summarized by the three-phase currents of the transformer, as follows:

$$I_{LCO} = \sum_{t=1}^{T} \sum_{p=a}^{c} I_t^p, \tag{19}$$

where I_t^p is the p phase current at the t-th time interval.

4.3. Constraints

The ranges of operating voltages for various loads in the Chinese National Standard (CNS) are shown in Figure 8. In this study, the operating voltages are restricted to within 95–105% of the nominal voltage for hybrid loads. The operating voltages for all the buses are restricted by,

$$\forall k \in \{1, 2, \cdots, m\}, \ \forall p \in \{a, b, c\} : 0.95 \leq V_{t,k}^p \leq 1.05. \tag{20}$$

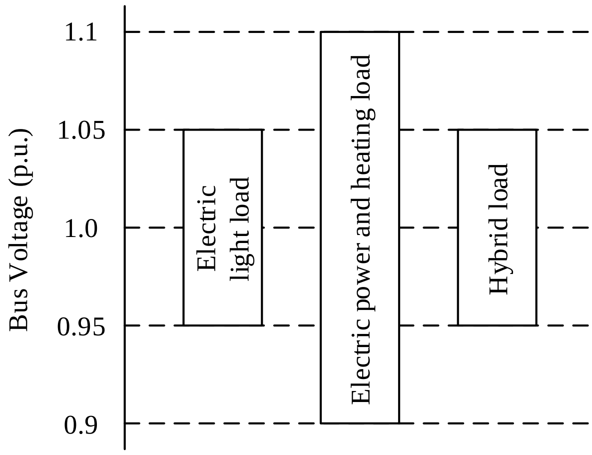

Figure 8. Voltage ranges for various load demands.

5. Results and Discussions

5.1. Sample System

In this study, according to the type of load and conductor, the sample residential distribution systems in Taiwan are shown in Figure 9. The sample distribution system can be classified into seven cases: (1) rural-underground cable (Feeder A); (2) rural-overhead line (Feeder B); (3) rural-mixed distribution of overhead primaries and underground laterals (Feeder C); (4) urban-underground cable (Feeder D); (5) urban-overhead line (Feeder E); (6) urban-mixed distribution of overhead primaries and underground laterals (Feeder F); and (7) total loads of feeding substation (Substation G). One-line diagrams of the sample distribution systems are shown in Figure 10. Tables 2 and 3 show the line segment and transformer data for Feeder A, respectively. For weekdays and weekends, the typical daily load curves obtained by load surveys for residential, commercial, and industrial section demands in the four seasons were used as load patterns. For the other sample cases, the network parameters proposed in [29] were used. The rearrangement of connection phases for a distribution transformer may require several hundred-dollar level fees. Compared with annual operating and maintenance costs, the rearrangement cost is relatively small. Furthermore, the optimal phase arrangement of distribution transformers connected to a primary feeder is an annual routine task for power utility. Not only power losses can be reduced, but also three-phase imbalance can be improved. Table 4 presents the system performance indices before rearranged structures for the typical residential distribution systems in Taiwan.

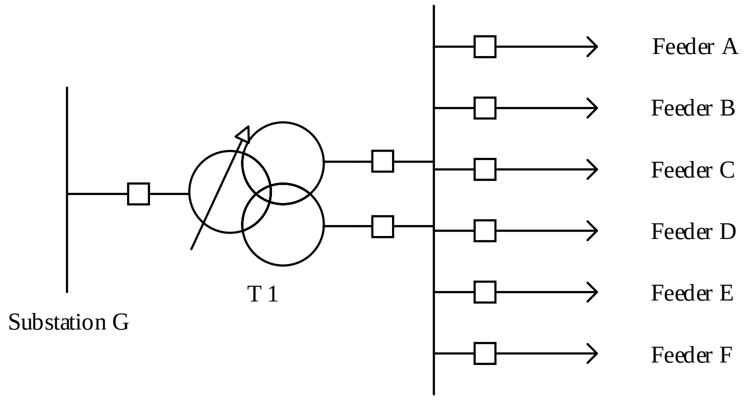

Figure 9. Schematic diagram of the sample distribution systems.

Table 2. Line segment data for feeder A.

Bus A	Bus B	Length (m)	Configuration	Phasing
G0	A0	0	500 MCM	ABCN
A0	A1	408	500 MCM	ABCN
A1	A2	520	#1 AWG	ABCN
A2	A3	1240	#1 AWG	ABCN
A3	A4	39	#1 AWG	ABCN
A4	A5	227	#1 AWG	ABCN
A1	A6	297	#1 AWG	CN
A3	A7	113	#1 AWG	BN
A3	A8	126	#1 AWG	AN

Table 3. Transformer data for feeder A.

No	Phasing	Connection	kV	kVA
T1	ABCN	Δ-GY	161-22.8	60 k-30/30 k
A1	AN	1Φ3W	22.8-0.22	25
A2	ABCN	GY-GY	22.8-0.22/0.38	50/50/50
A3	ACN	U-V	22.8-0.11/0.22	25/100
A4	AN	1Φ3W	22.8-0.11/0.22	167
A5	ABCN	GY-GY	22.8-0.22/0.38	167/167/167
A6	CN	1Φ3W	22.8-0.11/0.22	167
A7	BN	1Φ3W	22.8-0.11/0.22	167
A8	AN	1Φ3W	22.8-0.11/0.22	167

Table 4. Original system performance indices for the typical residential distribution systems in Taiwan.

	Feeder A	Feeder B	Feeder C	Feeder D	Feeder E	Feeder F	Substation G
TS_I	10,295,008.68	28,094,535.45	129,184,079.96	4,563,716.44	18,766,722.76	79,772,319.90	269,018,599.99
TL_L	89,865.14	136,965.79	690,089.60	377,748.38	439,961.60	1,152,073.82	2,969,153.53
AV_D	0.034568	0.002680	0.007152	0.059623	0.016666	0.017515	0.004486
Td_0	0.490072	0.420779	0.702016	1.023711	0.452849	0.524789	0.605306
Td_2	0.490050	0.325652	0.503149	0.369883	0.273289	0.528745	0.458602
I_{LCO}	176,636.49	473,256.39	1,186,076.21	174,289.97	560,205.82	1,244,200.53	1,829,289.09

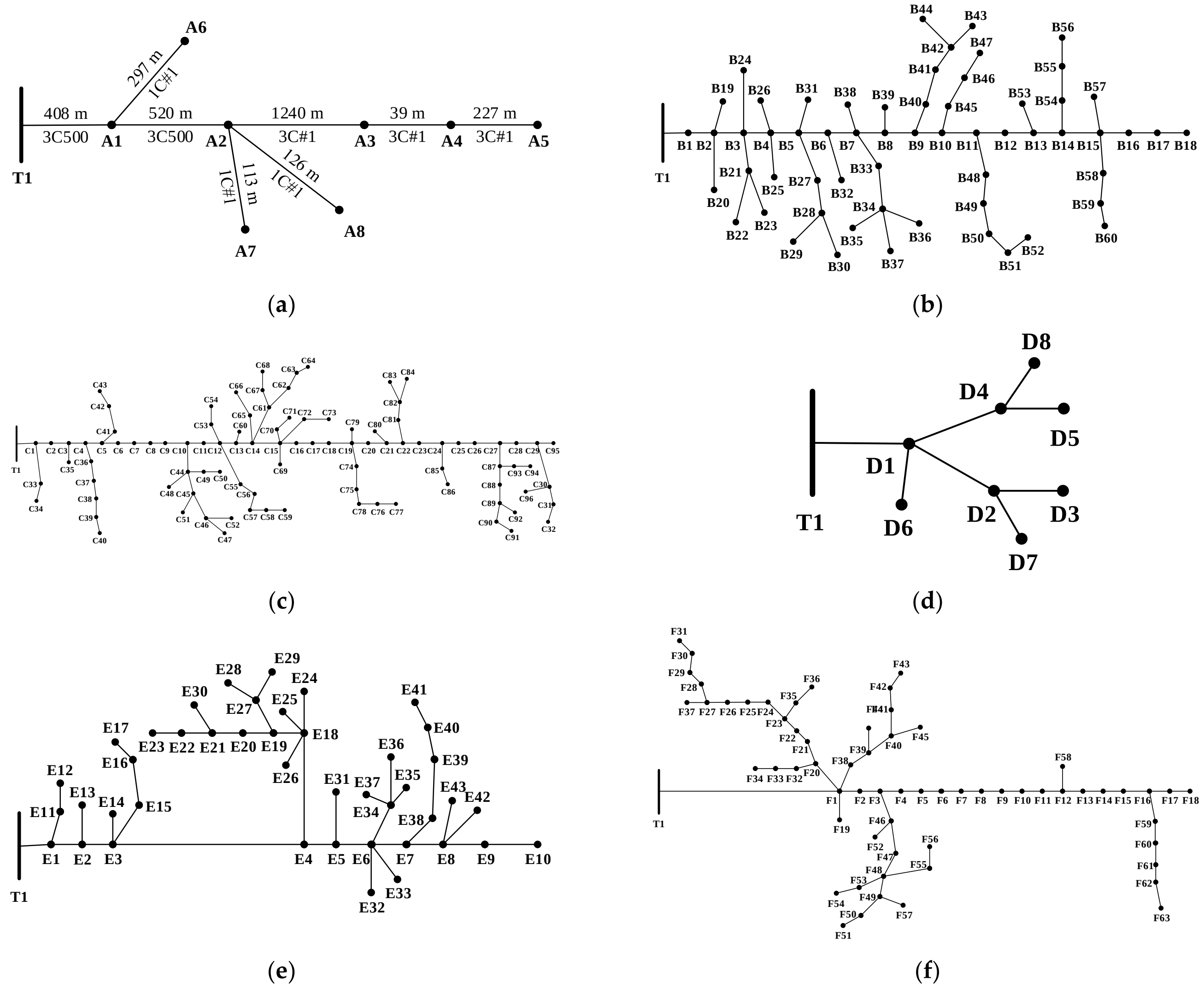

Figure 10. One-line diagrams of the sample distribution systems. (**a**) Feeder A-rural underground cable. (**b**) Feeder B-rural overhead line. (**c**) Feeder C-rural mixed distribution of overhead primaries and underground laterals. (**d**) Feeder D-urban underground cable. (**e**) Feeder E-urban overhead line. (**f**) Feeder F-urban mixed distribution of overhead primaries and underground laterals.

The above-mentioned typical sample systems in Taipower were used to evaluate the performance of the proposed approach. In addition, the possible improvement benefits of voltage quality and power loss for typical residential distribution systems in Taiwan can be determined. In this section, the parameters for the proposed NSGA-II-based approach are as follows:

1. Population size: 30;
2. Maximum iteration number: 100;
3. Crossover rate: 0.9;
4. Mutation rate: 0.1.

The service voltages for each typical sample distribution system are listed in Table 5.

Table 5. Service voltages in the sample distribution system.

Case	Service Voltage (p.u)
A, B	1.0
D, E	1.0125
C, F, G	1.025

5.2. Performance Study

In our previous work, a weight sum GA-based approach was used to optimize the phase arrangement of distribution transformers connected to primary feeders to improve three-phase imbalance and reduce power loss [16]. The previous work was extended to address the annual phase arrangement of distribution transformers for comparison purposes. The following are the parameters for the weighting-sum GA-based approach:

1. Population size: 30;
2. Maximum iteration number: 100;
3. Crossover rate: 0.9;
4. Mutation rate: 0.1.

Furthermore, multi-objective functions are transformed into a single objective function with weighting factors as follows:

$$Minimize\ FIT = \left(\omega_1 \frac{TS_I - TS_I^{\min}}{TS_I^{\max} - TS_I^{\min}} + \omega_2 \frac{TL_L - TL_L^{\min}}{TL_L^{\max} - TL_L^{\min}} + \omega_3 \frac{AV_D - AV_D^{\min}}{AV_D^{\max} - AV_D^{\min}} + \omega_4 \frac{Td_0 - Td_0^{\min}}{Td_0^{\max} - Td_0^{\min}} + \omega_5 \frac{Td_2 - Td_2^{\min}}{Td_2^{\max} - Td_2^{\min}} + \omega_6 \frac{I_{LCO} - I_{LCO}^{\min}}{I_{LCO}^{\max} - I_{LCO}^{\min}} \right) \quad (21)$$

Subject to

$$\omega_1 + \omega_2 + \omega_3 + \omega_4 + \omega_5 + \omega_6 = 1 \text{ and } \omega_1 = \omega_2 = \omega_3 = \omega_4 = \omega_5 = \omega_6.$$

System performance indices after carrying out the GA- and NSGA-II-based optimization processes for typical residential distribution systems in Taiwan are presented in Tables 6 and 7, respectively. Further comparison was performed between the system performance indices after carrying out the GA- and NSGA-II-based optimization processes. As presented in Table 8, the NSGA-II-based optimization process can provide a balance solution in most cases, especially for large-scale distribution networks with an amount of distribution transformers.

Table 6. System performance indices after carrying out the GA-based optimization process.

	Feeder A	Feeder B	Feeder C	Feeder D	Feeder E	Feeder F	Substation G
TS_I	10,088,628.12	18,297,666.97	83,248,486.23	4,639,218.44	12,990,382.72	67,624,326.41	224,091,182.95
TL_L	89,803.62	132,359.77	663,824.64	377,623.47	433,226.84	1,135,241.80	2,930,570.13
AV_D	0.033036	0.002752	0.005945	0.059621	0.015422	0.015920	0.003715
Td_0	0.489479	0.320050	0.405540	0.368660	0.270165	0.484816	0.498163
Td_2	0.487629	0.314341	0.428298	1.021781	0.298626	0.480212	0.431069
I_{LCO}	172,019.60	131,332.94	184,748.59	23,691.25	199,398.70	750,490.32	940,602.69

Table 7. System performance indices after carrying out the NSGA-II-based optimization process.

	Feeder A	Feeder B	Feeder C	Feeder D	Feeder E	Feeder F	Substation G
TS_I	10,073,007.39	15,997,059.15	76,606,334.11	4,644,979.03	10,231,665.00	70,252,501.37	204,807,841.65
TL_L	89,794.85	131,996.66	662,047.52	377,622.64	432,146.46	1,132,951.13	2,921,075.20
AV_D	0.033041	0.002756	0.005964	0.059620	0.014532	0.014791	0.003820
Td_0	0.489415	0.312421	0.422992	0.368644	0.258016	0.484871	0.516740
Td_2	0.487588	0.311024	0.395830	1.021782	0.336603	0.478832	0.388865
I_{LCO}	171,220.74	87,492.97	220,428.21	22,289.07	67,161.44	569,935.06	795,809.61

Table 8. Comparison of system performance indices after carrying out the GA- and NSGA-II-based optimization processes.

	Feeder A	Feeder B	Feeder C	Feeder D	Feeder E	Feeder F	Substation G
TS_I	0.16%	14.38%	8.67%	−0.12%	26.96%	−3.74%	9.42%
TL_L	0.01%	0.28%	0.27%	0.00%	0.25%	0.20%	0.33%
AV_D	−0.02%	−0.15%	−0.32%	0.00%	6.12%	7.63%	−2.75%
Td_0	0.01%	2.44%	−4.13%	0.00%	4.71%	−0.01%	−3.60%
Td_2	0.01%	1.07%	8.20%	0.00%	−11.28%	0.29%	10.85%
I_{LCO}	0.47%	50.11%	−16.19%	6.29%	196.89%	31.68%	18.19%

5.3. Comparison Study

For comparison, the initial chromosome and its corresponding genes were generated randomly. The chromosome consists of the genes of the connection schemes for load-tapped-off points. To evaluate the performance of the proposed NSGA-II-based approach for voltage imbalance improvement, the improvement rate (IR) was calculated using the following formula:

$$IR = \frac{x_{before} - x_{after}}{x_{before}}, \tag{22}$$

where x_{before} and x_{after} are the electrical quantities before and after performing the NSGA-II-based optimization process, respectively.

The improvement benefits of voltage quality and power loss for typical residential distribution systems in Taiwan are tabulated in Table 9. The influence and possibility of major factors influencing the improvement benefits for each case are as follows:

1. Feeder A: In this case, the typical distribution system is operated with low-load density and short-length feeders. This residential distribution system is the radial feeding of a collective housing area. The sample system has only eight distribution transformers, and the connection schemes of the three distribution transformers cannot be adjusted. Therefore, the improvements in voltage quality and power loss are limited by up to 5%.
2. Feeder B: In this case, the distribution system services low-load density areas with long-length feeders. This typical system feeds electricity demands for agriculture, animal husbandry, and aquaculture. Obviously, TS_I, Td_0 and I_{LCO} can be improved considerably in this case. The reduction in I_{LCO} was up to 80%. However, AV_D increased slightly because of the load balance effect. In other words, the phase current with a low load increases. Although the load demands of Feeder B are similar to those of Feeder A, the number of distribution transformers of feeder B is 7.5 times that of feeder A. Therefore, the improvement benefits in Feeder B are better than those in Feeder A.
3. Feeder C: In this case, the typical distribution system feeds the demands for residential, commercial, agricultural, and industrial electric energy. Compared with other benefit indices, the improvement benefits of TL_L and AV_D are not significant. However, the improvement benefits were the best among all the cases. The larger the scale of the distribution systems, the greater the potential for improvement benefits in voltage quality and power loss.
4. Feeder D: A high-reliability power service is required in a science and technology park. Usually, the behaviors of demand loads in a science and technology park are high-load density without the on-peak and off-peak periods. In this case, the typical distribution system is operated with a heavy load density and short-length feeders. The sample system has only eight distribution transformers, and the connection schemes of the distribution transformers cannot be adjusted significantly. The improvement benefits for Td_0 and Td_2 are in conflict. By suppressing the zero-sequence component of the distribution systems, Td_0 can be improved and I_{LCO} can be reduced. Therefore, in the proposed multiple-criteria decision making, two objective functions can be improved.

That is, the zero-sequence component of the distribution systems has a high priority for improvement.

5. Feeder E: In this case, a typical underground primary distribution system in an urban grid was investigated. Similar to Feeder D, the improvement benefits in Td_0 and Td_2 are conflicting in Feeder E. However, the number of distribution transformers of feeder E is greater than that of feeder D. More improvement benefits in voltage quality and power loss can be obtained in feeder E.
6. Feeder F: In this case, a typical distribution system feeds the demands for residential and commercial electric energy. After evaluating a series of case studies, qualitative results were obtained. Mixed distribution feeders with a large number of transformers and long-distance transmission have great potential for improving TL_L and AV_D.
7. Substation G: Substation G can be regarded as the summation of the above-mentioned six feeders. Therefore, as the individual feeders can be improved to balance as much as possible, substation G will achieve the best benefit, and its improvement benefit is less affected by the characteristics of the specific feeders.

Table 9. Improvement benefits of system performance indices after carrying out the NSGA-II-based optimization process.

	Feeder A	Feeder B	Feeder C	Feeder D	Feeder E	Feeder F	Substation G
TS_I	2.16%	43.06%	40.70%	−1.78%	45.48%	11.93%	23.87%
TL_L	0.08%	3.63%	4.06%	0.03%	1.78%	1.66%	1.62%
AV_D	4.42%	−2.86%	16.62%	0.00%	12.80%	15.55%	14.84%
Td_0	0.13%	25.75%	39.75%	63.99%	43.02%	7.61%	14.63%
Td_2	0.50%	4.49%	21.33%	−176.24%	−23.17%	9.44%	15.21%
I_{LCO}	3.07%	81.51%	81.42%	87.21%	88.01%	54.19%	56.50%

6. Conclusions

In this study, the problems caused by a three-phase voltage imbalance were first introduced. The principle of the NSGA-II-based approach was then briefly described. With the characteristics of a fast non-dominated sorting approach, a parameterless diversity-preserving approach, an elitist strategy, and a simple and effective constraint-handling approach, the proposed NSGA-II-based approach can be effectively used to evaluate and analyze the improvement benefits of typical residential distribution systems.

The system operation conditions may have a significant effect on the improvement benefit of the load balance strategy. In this study, the system service voltages for all load points satisfy the requirements of the rules in a year. The system service voltages in typical residential systems are set between 1.0 and 1.03 p.u. of nominal voltage. The larger the scale of the distribution systems, the more potential improvement benefits in voltage quality and power loss. Using the proposed method, the total power imbalance, total line loss, average voltage drop, total voltage imbalance factor, and neutral current of the main transformer can be improved considerably.

In this study, a set of typical daily load curves for residential, commercial, and industrial section demands in four seasons was used as load patterns to evaluate the annual phase arrangement of distribution transformers connected to primary feeders. Therefore, typical improvement benefits for typical residential distribution systems in Taiwan can be obtained. The results of this study can be applied for energy saving, and can aid the authorities in implementing sustainable development policies in Taiwan. In future work, the load demands recorded by supervisory control and data acquisition (SCADA) can be further used to evaluate the annual phase arrangement of distribution transformers for a specified residential distribution system.

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