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Optimal Phase Selection Of Single-Phase Appliances In Buildings Using String-Coded Genetic Algorithm

Novalio Daratha*[1], Arie Vatresia[2], Hendy Santosa[3], Indra Agustian[4], Dedi Suryadi[5], Neeraj Gupta[6]

[1,3,4]Electrical Engineering Department, University of Bengkulu, Indonesia
[2]Informatics Department, University of Bengkulu, Indonesia
[5]Mechanical Engineering, University of Bengkulu, Indonesia
[6]Electrical Engineering Department, National Institute of Technology Srinagar, India

Email: [1]ndaratha@unib.ac.id

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Abstract

Phase imbalance in buildings, primarily caused by single-phase loads and generation, leads to increased neutral current, voltage imbalance, reduced energy efficiency, and potential equipment damage. To address these challenges, an optimal phase selection method is proposed for single-phase loads and generation. This method integrates integer programming with a string-coded genetic algorithm (GA). The GA employs string encoding to represent phase connections. Initially, a Mixed Integer Programming (MIP) solver identifies an initial solution, which is subsequently transformed into a string to initialize the GA's genes. Subsequently, the GA executes standard operations such as mutation, crossover, evaluation, and selection. Case studies demonstrate the efficacy of this method in achieving substantial load balancing. Notably, the identification of multiple solutions with identical objective function values renders this approach suitable for smart buildings equipped with energy management systems that participate in ancillary services between low-voltage and medium-voltage networks. This research pertains to the domains of computer science, power engineering, and energy informatics.

Keywords: *Building energy management, Genetic Algorithm, Low voltage network, Single-phase appliance, Unbalanced load.*

NOMENCLATURE

$\lvert a \rvert$	Length of a string named a.
b_i	The upper limit of i^{th} inequality constraint.
$f_0(\mathbf{x})$	Objective function.
$f_i(\mathbf{x})$	the i^{th} inequality constraint function.
$g_j(\mathbf{x})$	the j^{th} equality constraint function.
$L(a,b)$	Leveinstein distance between a string a and another string b.
LV, LVN	Low Voltage, Low Voltage Network.
N	Total number of single-phase appliances.
N_P	Number of individuals in the population used in Genetic Algorithm.
MIP	Mixed Integer Programming.
$\mathbf{P}$	$N \times 1$ vector of power consumptions of appliances.
P_i	Power consumption of the i^{th} appliance.

$Pave$	Average power per phase.
$\tau(s)$	A function that gives all but the first element of a string s.
U_ϕ	Unbalance indices for phase $\phi \in \{r,s,t\}$.
$\mathbf{x}$	the $N \times 1$ vector of variables of optimization where $x_i \in \{r,s,t\}$ represent the phase at which the i^{th} load is connected. The variable $\mathbf{x}$ is also a string.
$\mathbf{x}j$	the variable of optimization corresponds to the j-th individu within Genetic Algorithm.

1. INTRODUCTION

In buildings with three-phase electric power supply, there is a common problem of unbalanced distribution of load among three phase because many loads are single-phase devices such as lighting, computers, small appliances and single-phase motors [1], [2]. This unbalanced load cause many problems in the corresponding distribution networks such as network capacity waste, unbalanced-induced energy loss, unbalanced-induced nuisance tripping, and motor overheating and damages [1], [3].

Load balancing can be performed by utilities or consumers. For instance, utilities can implement optimal phase arrangements of distribution transformers, static phase switching devices [4] and install static VAR compensators or DSTATCOM [5]. When managed by utilities, load balancing is executed at the network level [6], [7], [8], [9]. Conversely, customers can balance their loads by controlling plug-in electric vehicles (PEV) [8], [10] and energy storage systems. When done by customers, phase balancing can be performed at the building level [8], [11], [12], [13].

Most previous works have focused on the utility side, resulting in limited literature on phase balancing within buildings [14]. For example, some studies such as [6], [9], [14], [15], [16] have considered re-phasing of single-phase loads in low-voltage networks. In such studies, each load is a combination of all appliances in a building which can be single-phase, two-phase or three-phase loads. Re-phasing of these loads can reduce line losses. However, these studies do not take into account individual appliances within buildings.

Furthermore, there are also studies focused on appliances within buildings that have a three-phase supply. Those studies show that balancing loads in buildings with three-phase supplies has been recognized as a potential service provided by flexible customers. Recently, an incentive scheme has been proposed that offers contribution-based remuneration suitable for small to medium-sized customers for phase balancing service [17]. In addition, there is also works toward home participation in reduction of voltage unbalance [8]. In addition, paper [18] proposes a framework in which new ancillary services can be provided by a building with capability as proposed here. The framework includes three stages in which model predictive control is used to determine the set points given to buildings with flexibility. It is our view that our work can be used by buildings participating in the frame work.

Based on previous discussion, the phase balancing in existing studies is done at utility levels. This paper focuses on phase balancing in buildings. This paper complements [17] and [8] by exploring way to control the phase at which each appliance is connected. In addition, phase balancing as ancillary service is proposed in [18]. Note that the works in [12], [19], [20], [21] also consider appliances but do not consider phase balancing. Hence, phase balancing by building is underexplored research topic.

This paper proposes a method to select the phase at which a single-phase electric appliance is connected to distribute all appliances within a building supplied with a three-phase four-wire low-voltage (LV) feeder. It is formulated as an optimization problem, where a solution represents the phase to which each load in the building is connected. The method employs a string-coded genetic algorithm, unlike the one in [22], [23].

The rest of this paper is organized as follows. Section 2 formulates the problem as an optimization. Section 3 describes the proposed method. Section 4 discusses the results of simulations. Finally, Section 5 concludes this paper.

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2. METHODS

In building with 4-wire (r, s, t phases wire and a neutral wire) three-phase electricity supply, phase unbalance can be caused by unequal allocation of single-phase load and generation, random load behaviour, network structural asymmetry, and unbalance faults. The unbalance has several consequences such as unused network capacity and corresponding cost, addition losses in phase, neutral, ground and transformers conductors, nuisance tripping, low operation efficiency, overheating, damages in induction motors [1]. The proposed method is aimed at addressing:

1. the unequal allocation of loads and generation.
2. with phase switching devices such as one in [24], random load and generation behaviour.

We formulate an optimization problem in which the phase at which a single-phase load or generation is optimized to reduce phase unbalance to minimum (zero if possible or small number).This Section describes how to solve the phase balancing problem using a combination of MIP solver and genetic algorithm [22], [23].

It assumed that each appliance (each group of appliances) is supported by a phase switching device (PSD) similar to the one in [7] which enable it to transfer for one phase to another phase as requested by a controller. We try to select optimal phase for each PSD which minimize the power mismatch between the calculated and target value

2.1. Optimal Phase Selection Problem

Optimal phase selection of single-phase appliances in a building is formulated as an optimization problem, as shown in Equation (1):

$$\begin{aligned} \underset{\mathbf{x}}{\text{minimize}} \quad & f_0(\mathbf{x}) \\ \text{subject to} \quad & f_i(\mathbf{x}) \leq b_i,\ i = 1,\dots,m. \\ & g_j(\mathbf{x}) = 0,\ j = 1,\dots,n. \end{aligned} \tag{1}$$

where $\mathbf{x}$, f_0, f_i, and g_j represent the optimization variables, objective function, inequality constraints, and equality constraints, respectively. The equality g_j constraints represent:

- An appliance connects to only one phase.
- Definition of total power per phase.
- Definition of average power.

The inequality constraints f_i model, for example, the limit on imbalance or the number of switching.

1) Variables and Parameters: The optimization variables corresponding to the i-th appliance $x_i \in \{r,s,t\}$ represent phases at which it is connected. The solution of the optimization problem, x^*, represents the optimal phase connection of each appliance in a building.

In addition, power consumption of those appliances are represented by a vector

$$\mathbf{P} = [P_1, P_2, \dots, P_N]^T \tag{2}$$

where P_i represents the power consumption of the i-th appliance and N is total number of appliances. Without loss of generality, the value of P_i is selected from the rated power of i-th appliance. [1]

2) Objective Function: In order to phase unbalance, we minimize maximum values of power unbalance index. Hence, the objective function is given in (3)

$$f_0(\mathbf{x}) = \max_{\mathbf{x}}\{U_r, U_s, U_t\} \tag{3}$$

where the power imbalance indices U_r, U_s and U_t are given in Eqs. (4)

[1] In fact, power in Eq. (2) can be replaced with current as in [25], and the resulting problem can be solved similarly.

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$$U_{\phi}(x) = 100\left|\frac{P_{tot}^{\phi}-P_{ave}}{P_{ave}}\right|, \phi = \{r,s,t\} \tag{4}$$

where P_{tot}^{ϕ} is the total power of all loads connected to phase ϕ and P_{ave} is the average power as given in (5).

$$P_{ave} = \frac{\sum_{i=1}^{N} P_i}{3}. \tag{5}$$

Without loss of generality, we assume that each P_i is a constant and, hence, P_{ave} is also a constant.

3) Constraints: The total power of appliances connected at phase ϕ, P_{tot}^{ϕ} , is given by Eq. (6)

$$P_{tot}^{\phi}(x) = \sum_{i=1}^{N} P_i \text{ if } x_i = \phi \tag{6}$$

Based on the above equations, the optimal phase selection problem can be represented as (7).

minimize Eq.(3)
subject to Eqs.(4) − (6) (7)

2.2. An MIP Approach

An MIP solver uses numerical values for optimization variables. Hence, we need modifications in the formulation. We use a binary $3\ x\ N$ matrix **y** where $\mathbf{y}_{ij} \in \{0,1\}, i \in \{1,2,3\}, j \in \{1,2,3,\dots,N\}$. Then we can define objective function as (*8*) and constraints as (*9*),(*10*),(*11*), and (*12*). Note that a constraint ((*12*)) ensures that each load connects to a phase only.

$$\min_{y} U_{max} \tag{8}$$

subject to

$$U_i \le U_{max} \tag{9}$$

$$U_i \ge 100\frac{P_{tot}^{\phi} - P_{ave}}{P_{ave}} \tag{10}$$

$$-U_i \ge 100\frac{P_{tot}^{\phi} - P_{ave}}{P_{ave}} \tag{11}$$

$$\sum_{i=1}^{3} y_{ij} = 1 \forall j \in \{1,2,3,\dots,N\} \tag{12}$$

2.3. Optimization using MIP solver

Consider a scenario where *n* single-phase appliances are to be connected to a three-phase network. The power ratings of these appliances are listed in Table I. The objective is to determine the phases to which each appliance should be connected in order to minimize power imbalance.

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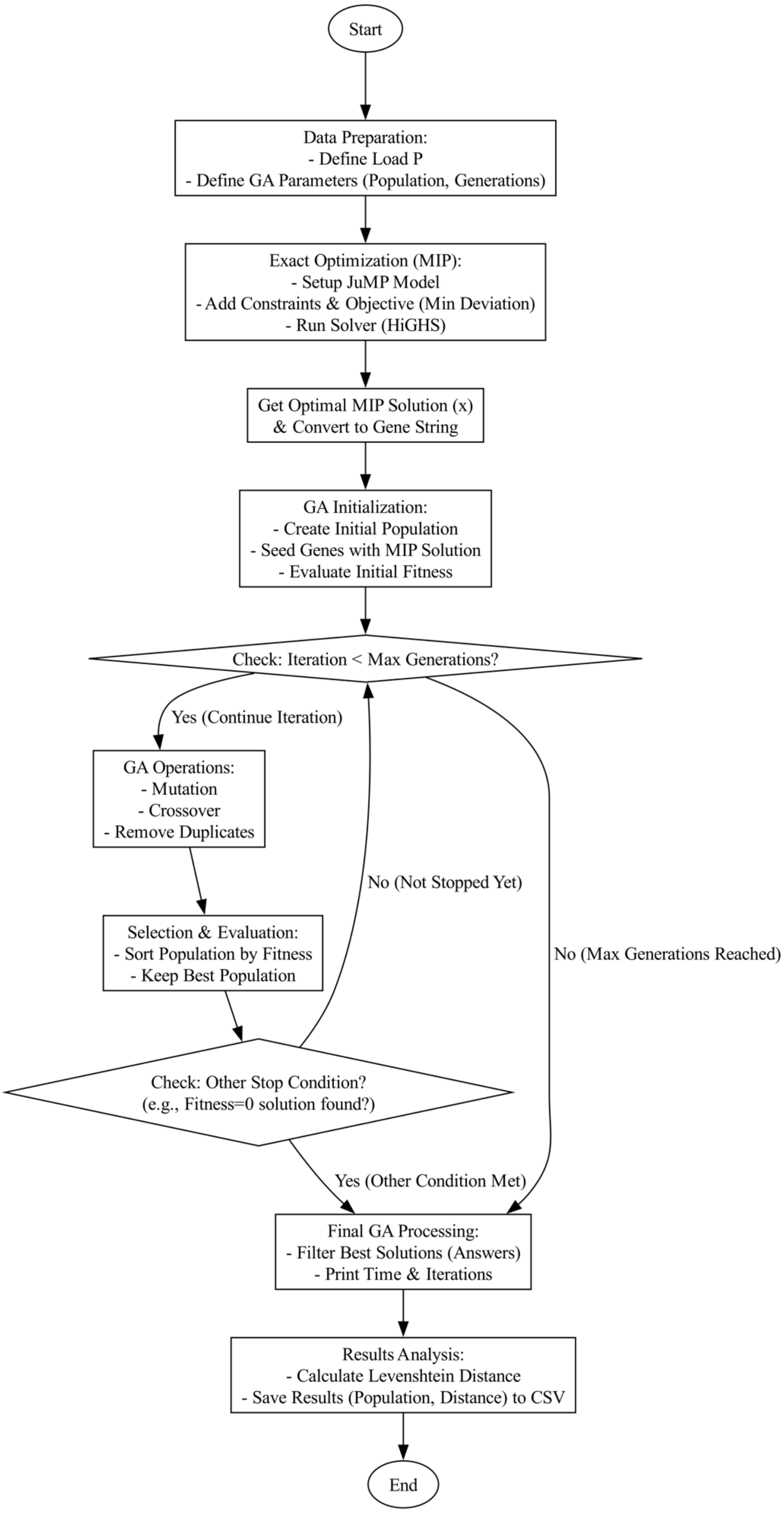

Figure 1. Genetic Algorithm Process for Optimizing Phase Selection.

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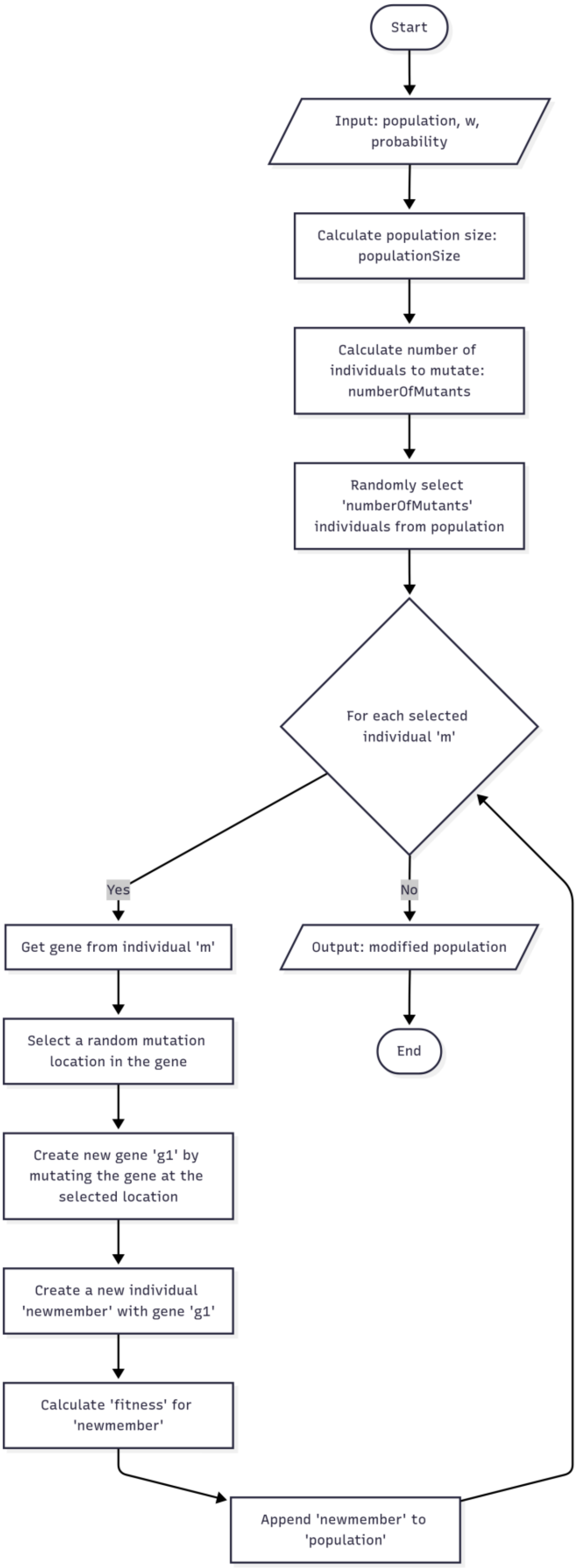

Figure 2 All steps done during mutation proses.

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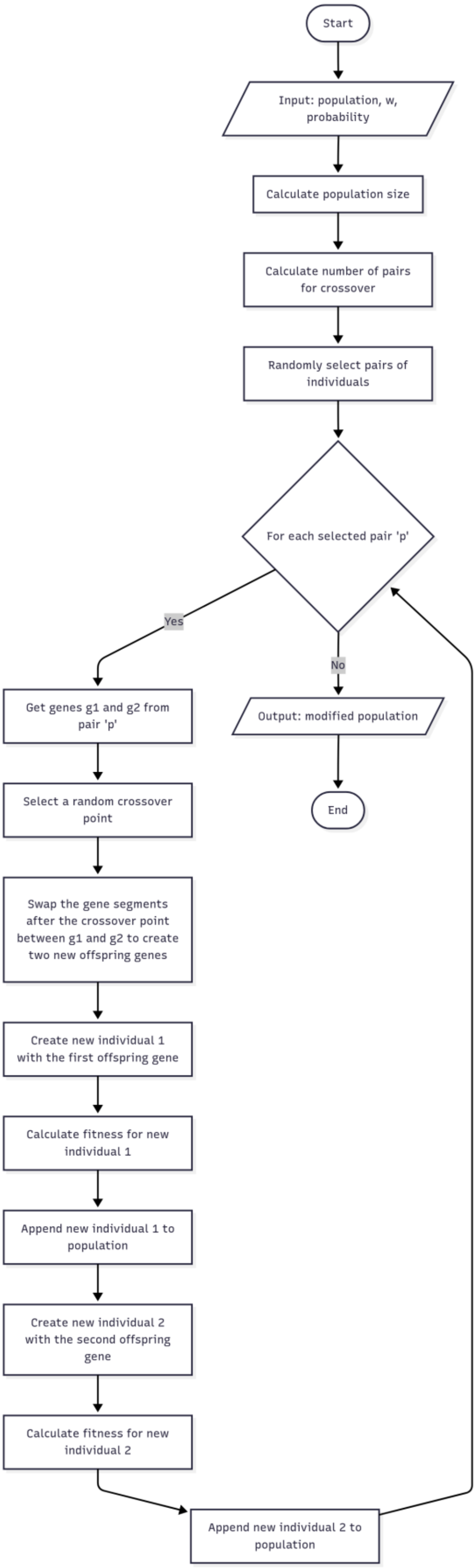

Figure 3 All steps done during crossover process.

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Each appliance can be connected to one of the three phases, denoted by the set $\{r,s,t\}$. The challenge is to find permutations that result in the smallest imbalance. Since the total number of possible permutations is 3^n, performing an exhaustive search is *impractical* for large values of n. By using a Mixed Integer Linear Programming solver (HiGHS [26]) repeatedly, one solution, *ssssssrrst*, was found after 1000 runs. The total installed power on phases s, r, and t are 379 W, 496 W, and 740 W, respectively. The proposed method (see Section III) identifies 282 optimal solutions. One such solution, *rrrrrrsst*, is presented in Table I, which results in total installed loads of 449 Won phase r, 426 W on phase s, and 740 Won phase t.

The two examples have identical objective function values, as illustrated in Table II. This indicates that the problem has multiple solutions. In general, most solvers, such as CPLEX, Gurobi, GLPK, and HiGHS are designed to find a solution. Consequently, they do not provide alternative solutions if the problem is multimodal. To address this limitation, this paper proposes an approach that employs a genetic algorithm to discover these solutions.

2.4. Optimization using MIP solver and Genetic Algorithm.

Figure 1 shows the method proposed in this paper. Many steps are well-known in literature. Saving space, we review only relevant steps in the following.

1. *String-coded Variables:* The optimization variables are represented by $\mathbf{x} = x_1x_2x_3 \ldots x_N$ where N is the number of single-phase appliances and $x_i \in \{r,s,t\}$ for $i = 1,2,..,N$. In our implementation, the optimization variable is a *non-numeric* string. This encoding has some benefits compared to numerical encoding used in [22], [23]. Firstly, since the value of the optimization variables are not numbers i.e. r, s, or t, it is natural to use non-numeric encoding. Secondly, the constraint in (*12*) is not needed.
2. *Initialization of population:* An initial population $X = [\boldsymbol{x}^1, \boldsymbol{x}^2, \boldsymbol{x}^3, \ldots, \boldsymbol{x}^{N_p}]$ having N_p individuals can be generated. Each of $\boldsymbol{x}^j = x_1x_2x_3\ldots x_N, j \in \{1,2,\ldots,N_p\}$ represents the j-th individual which corresponds to a possible connection scenario. Hence the population is represented as list of strings. For example, the following list,
$$X = [x1, x2, x3] = [rrr, sss, ttt] \in \{rrr, rrs, rrt, \ldots, ttt\},$$
represents a situation in which there are three individuals. each represents connections of 3 loads. In the proposed method, the solution of the MIP given in (8) becomes starting values of all members of the initial population.
3. *Evaluation of individual fitness:* Fitness evaluation calculates the objective function in eq. (3) based on the string x^j and the vector **P**.
4. *Mutation:* Mutation is done based on probability of mutation Pm. The total number of mutants is given by $N_m = P_m N_p$. The N_m mutants are randomly selected. If an individual $\boldsymbol{x}^j$ is selected to be a mutant, a gen of $\boldsymbol{x}^j$ is changed randomly. Steps done is Mutation as shown in Figure 2 are:
   a. **Start**: The process begins with the mutation function call.
   b. **Input**: The function receives population, w, and probability as input.
   c. **Calculate Population Size**: Calculates the total number of individuals in the population.
   d. **Calculate Number of Mutants**: Determines how many individuals will be mutated based on populationSize and probability.
   e. **Select Random Individuals**: Randomly selects which individuals from the population will be mutated.
   f. **Loop (For each individual)**: A loop begins for each individual selected for mutation.
   g. **Get Gene**: The gene of the individual being processed is taken for modification.
   h. **Select Mutation Location**: A position within the gene is randomly selected as the mutation point.
   i. **Create New Gene**: A new gene (g1) is created by changing the original gene at the selected location.

j. **Create New Individual**: A new individual (newmember) is formed using the mutated gene (g1).
k. **Calculate Fitness**: The fitness value for the new individual is calculated.
l. **Append to Population**: The newly processed individual is added to the initial population.
m. **Return to Loop**: The process returns to step 6 to process the next selected individual. If there are no more individuals to process, the loop stops.
n. **Output**: After the loop finishes, the function returns the population, which now contains the new individuals resulting from the mutation.
o. **End**: The process ends.

5. *Cross Over:* The probability of crossover is P_c. Hence, the expected number of pairs doing cross-over is $P_c N_p$. Each pair and the point of cross over are selected randomly. Steps done is crossover as shown in Figure 3 are:
   a. **Start**: The process begins.
   b. **Input**: The function receives the population, w, and probability for crossover.
   c. **Calculate Population Size**: Determines the total number of individuals.
   d. **Calculate Number of Pairs**: Calculates how many pairs will undergo crossover based on the probability.
   e. **Select Pairs**: Randomly selects pairs of individuals from the population.
   f. **Loop**: A loop starts for each selected pair.
   g. **Get Genes**: The genes (g1, g2) from the two parent individuals in the pair are retrieved.
   h. **Select Crossover Point**: A random position within the gene is chosen as the point for the swap.
   i. **Swap Segments**: The parts of the genes after the crossover point are exchanged between the two parents, creating two new offspring genes.
   j. **Create & Process Offspring 1**: A new individual is created from the first offspring gene, its fitness is calculated, and it's added to the population.
   k. **Create & Process Offspring 2**: The same process is repeated for the second offspring gene.
   l. **Return to Loop**: The process continues with the next pair.
   m. **Output**: Once all pairs have been processed, the function returns the updated population, which now includes the new offspring.
   n. **End**: The process is complete.
6. *Selection:* Mutation and crossover create new individuals. If all new individuals is unique, the total number of individuals is $N_P(1 + P_m + P_c)$. If there are duplicates of previous individuals, they will be deleted. Further, they are ranked based on their fitness values. To capture as many solutions as possible, the population is allowed to increase up to a number N_P^{max}. the Top N_P individuals are selected as the new members of the population. Then, the next iteration begins.
7. *Stopping Criteria:* The iteration continues until one of the following occurs:
   a. there are at least N_{opt} individuals whose fitness values are less than a small number ϵ.
   b. the total number of iterations is reached.

3. RESULTS

The proposed method is implemented using Julia programming language. The MIP part is done using JuMP and HiGHS. The proposed method is implemented using Julia language using parameters given in Table 1. Simulations were done using a laptop with Mac OS, M4 CPU , 16 GB memory. These parameters are chosen based on trial-and-error approach.

Table 1 Parameters of GA Used in Simulations

No	Name	value
1	Initial population size	1000
2	Number of generations	50
3	Mutation probability	0.8
4	crossover probability	0.8

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This section discusses the results of several simulations. The first simulation describes a small case and shows that the problem has many solutions. The second simulation shows how the proposed method can be used in an academic building with assumption that all appliances consume their rated power respectively. The third simulation discusses a bigger problem on multistorey building. We discuss some issue related to randomness of usage of those appliances.

3.1. *Case 1a:* Small *examples with multiple global optima*

This subsection discusses a small case in which there are six appliances with rated power of 1 W, 2 W, 3 W, 4 W, 5 W and 6 W respectively. The corresponding power vector is given by

$$\mathbf{P} = [P_1\ P_2\ P_3\ P_4\ P_5\ P_6] = [1\ 2\ 3\ 4\ 5\ 6].$$

The corresponding optimization variable is

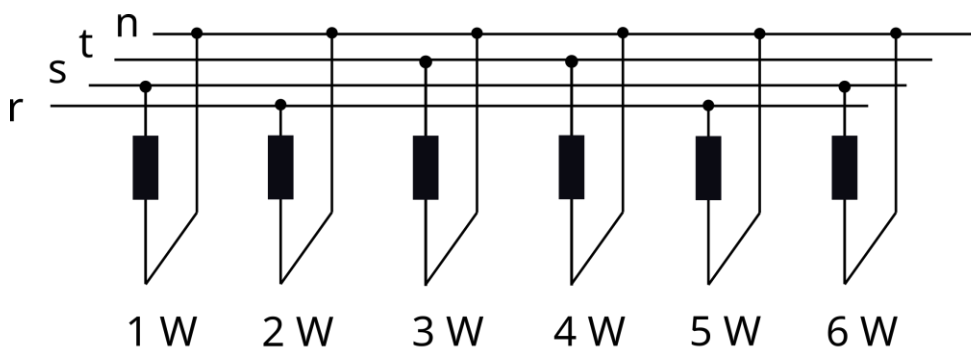
$$\boldsymbol{x} \in \{rrrrrr, rrrrrs, rrrrrrt, \dots, ttttttt\}.$$

In this instance, there are 3^6 permutations corresponding to potential phase connections. The proposed method successfully identifies six solutions, as detailed in Table 2. For illustration, Figure 4 shows how to implement of the solutions into actual connections. Consequently, the balancing problem may present multiple solutions.

Furthermore, Table 3 shows number of solutions with objective function equal zeros, $f_0 = 0$, and total number of permutation for $P = [1\ 2\ 3\ \dots\ N]$, $N \in \{6, 9, 12, 15\}$. The number of solutions are less than 1% of size of all permutations. Hence, as with other combinatorial problems, the number of solutions is a small percentage of the search space.

Table 2 Several Options With Perfect Balance For P = [1 2 3 4 5 6]T (Figure 4 illustrates Connections Corresponding To Solution Number 4).

No	Phase loads	$\boldsymbol{x}$ ($N = 6$)
1	R= { 1, 6, },S={ 2, 5, },T={ 3 4 }	rsttsr
2	R= { 1, 6, },S={ 3, 4, },T={ 2 5 }	rtsstr
3	R= { 2, 5, },S={ 1, 6, },T={ 3 4 }	srttrs
4	R= { 3, 4, },S={ 1, 6, },T={ 2 5 }	strrts
5	R= { 2, 5, },S={ 3, 4, },T={ 1 6 }	trssrt
6	R= { 3, 4, },S={ 2, 5, },T={ 1 6 }	tsrrst



$$C_p = srttrs$$

Figure 4 Connections of loads with optimal balance correspond to the third solution given in Table 2.

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Table 3 Comparison Of Number Of Zero Solution For P = [1 2 3 ... N], N = 6,9,12.

No	N	No of solutions (N_s)	$100\frac{N_s}{3^N}$
1	6	6	0.82
2	9	54	0.27
3	12	612	0.12
4	15	8878	0.06

3.2. Case 1b: small case but realistic situation.

This case illustrates a small but realistic situation in a room in a large building. It is usual practice in many places that all these appliances are connected to a phase. **Table 4** shows appliances in that room. If three-phase supply is available in such room, they can be balanced using the proposed method. An MIP solver gives only one solution. On the other hand, the proposed method can find 282 solutions all of which has the same values of unbalanced index.

In comparison, both case 1a and 1b have 9 appliances. Case 1a has optimal solutions with perfect balanced phase connection. However, the optimal situation in Case 1b has unbalanced distribution between phases.
Table **5** shows the solution correspond to MIP solver and one solution correspond to the proposed methos.

Table 4 Example of Power Consumption of Several Electric Appliances and Their Balanced Phase Connections

No	Name	Power Rating (W)	Phase connection*
1	LED lamp	18	r
2	LED lamp	22	r
3	LED lamp	15	r
4	Refrigerator	116	r
5	Computer 1	88	r
6	Computer 2	190	r
7	Computer 3	189	s
8	Computer 4	237	s
9	Air conditioner	740	t

Table 5 Values of Unbalance Indices of Case 1b.

solution	U_r	U_s	U_t	f_0	solver
ssssssrrst	29.6	7.9	37.5	37.5	MIP solver
rrrrrrsst	16.6	20.9	37.5	37.5	One of solution by the proposed method

3.3. *Case 2: A two-story building*

This subsection reports results corresponding to a building in Germany . The loads considered are listed in Table 6. In total, there are 74 devices. Each of them participates in the optimization. The values of parameter P given in Eq. (2) are rated powers as given in the table. The initial MILP is solved using HiGHS solver. The solution is "srrtrttrstrtttsrrttttrsttttttsttttrttttrtttttttrststtsrtttrrrssttttttttttt ttt". The corresponding objective value is 0.015. The solution is used as an individual in the first population in Genetic Algorithm. The parameters of GA are given in Table VI.

There are 10000 solutions corresponding to the same objective values. On the hand, the size of search space is 3^{74}. Hence, the number of found solutions is a small portion of the search space. Consequently, proposed method can be used as screening approach before doing optimization which consider network impedance.

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Table 6 Electric Loads In An Academic Building For Case 2 [27].

Class	Manufacturer	Type	Power (w)	Count	Symbol
2*Battery Charger	Kraftmax	BC4000 Pro	18	1	P_1
	DJI	Phantom 3	100	1	P_2
Daylight	Philips	HF3430	10	1	P_3
4*Desktop Computer	generic	Intel Xeon E5-1640 v4, NVIDIA TITAN X	1200	1	P_4
	Dell	OptiPlex 7040	65	1	P_5
	Dell	OptiPlex 9020	65	2	P_6, P_7
	Dell	T3600	635	1	P_8
3*Dev Board	FPGA	Xilinx ML505	30	1	P_9
	FPGA	Tegra Jetson	90	1	P_{10}
	MEDAL	Prototype	5	1	P_{11}
Electric Toothbrush	generic	inductive charging	5	1	P_{12}
2*Fan	Eurom	VS 16	45	1	P_{13}
	VOV	VTS-1641	50	1	P_{14}
2*Kettle	Clatronic	WK3445	2000	1	P_{15}
	Severin	WK3364	1800	1	P_{16}
17*Laptop Computer	Apple	MacBook Air 13" Early-2014	45	1	P_{17}
	Apple	MacBook Pro 13" Mid-2014	60	3	$P_{18}, \dots, P_{20}$
	Apple	MacBook Pro 15" Mid-2014	85	2	$P_{21}, \dots, P_{22}$
	ASUS	N750JV	120	1	P_{23}
	Dell	E6540	130	1	P_{24}
	Dell	XPS13	45	1	P_{25}
	Lenovo	Carbon X1	90	1	P_{26}
	Lenovo	B560	65	1	P_{27}
	Lenovo	L540	90	1	P_{28}
	Lenovo	T420	90	1	P_{29}
	Lenovo	T450	65	1	P_{30}
	Lenovo	T530	90	1	P_{31}
	Lenovo	X230 i7	65	1	P_{32}
	Lenovo	X230 i5	170	1	P_{33}
	Schenker	W502	180	1	P_{34}
	Sony	Vaio VGN FW54M	92	1	P_{35}
	generic	SMPS, 19V	100	1	P_{36}
5*Monitor	Dell	P2210	22	1	P_{37}
	Dell	U2711	133	6	$P_{38}, \dots, P_{43}$
	Dell	U2713Hb	130	8	$P_{44}, \dots, P_{51}$
	Dell	UP2716D	45	2	P_{52}, P_{53}
	Fujitsu-Siemens	P17-1	36	1	P_{54}
Multi-Tool	Mannesmann	M92577	135	1	P_{55}
Paper Shredder	HSM	Shredstar	250	1	P_{56}
Printer	HP	LaserJet Pro 400	425	1	P_{57}

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Projector	Epson	EB-65950	450	1	P_{58}
Screen Motor	Projecta	DC 485	210	1	P_{59}
Space Heater	Heller	ASY 1507	1500	1	P_{60}
10*USB Charger	generic	single USB power adapter	10	2	P_{61}, P_{62}
	inateck	UC2001	15	1	P_{63}
	Aukru	BS-522	20	1	P_{64}
	Apple	MD836ZM EU	12	1	P_{65}
	Apple	MD813ZM EU	5	2	P_{66}, P_{67}
	Chromecast	single USB power adapter	10	1	P_{68}
	Hama	91321	10	1	P_{69}
	Samsung	Travel	10	3	$P_{70}, \ldots, P_{72}$
	Sony	single USB power adapter	10	1	P_{73}
	Sony Ericsson	EP 800	10	1	P_{74}

3.4. *Case 3: Multistories Building*

There is a challenge in finding the values for parameters P given in Eq. (2). When online measurements are available, real-time values can be used. However, in many cases, online measurements is very limited. Hence, each value in parameters P can represent a device or a group of devices.

Grouping of devices can be based on location or their type. It reduces the size of optimization problem. Hence, in situation with large number of devices this approach is effective. Appliances in a building can be grouped into zones and categories as shown in Table VII which represents a building in Thailand [28]. Assume that each zone in the building is supplied with three-phase four-wire circuits, we can divide all appliancess into

1) Air Conditioners: Each AC corresponds to a control variable.
2) Lighting: All lighting loads in a zone are grouped and corresponds to a optimization variable.
3) Plug: All appliances other than AC and sensors in a zone and corresponds to a optimization variable.
4) sensor: All sensors or another always-on devices and correspond to a optimization variable.

As shown in Table 7, on Floor 1, there are 4 zones. There are 4 air conditioners which are all installed in Zone 2. All zones have lighting loads but none has sensor loads. Zones 2,3,4 have plug loads. In total, there are 11 measurements of powers in kW every minute in 2019.

In this kind of situation, what are the values for P given in Eq (2)? The answer is *not* the total number of rated power of all devices in a group. The reason is that those devices do not active at the same time as indicated in Figure 5 which shows the histogram of lightning loads in four zones on a floor. Those Histograms indicate variation of probability density functions for total zonal lighting loads in the floor. Hence, this proves that using the sum of rated power all devices within a zone in general as P is probably not accurate.

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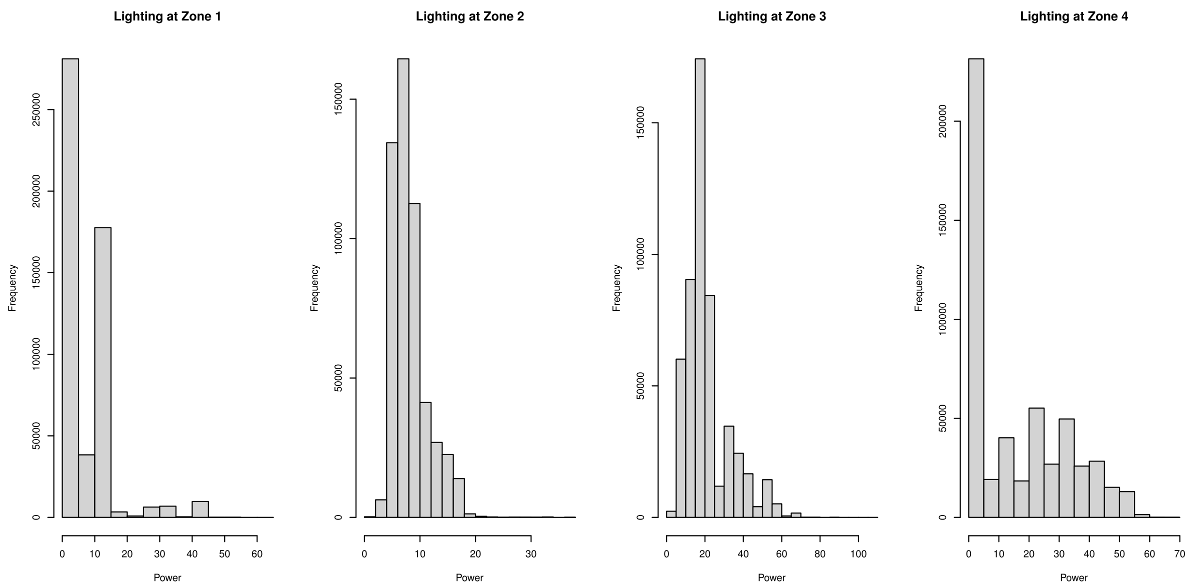

Figure 5.Histogram of power consumption for lighting purpose at four zones in the first floor of an academic building in UC Thailand. Based on per minute data from 1 January 2019 to 31 December 2019.

Table 7 Load Distribution In A Building In Thailand [28].

Floor	Zone	AC	Light	Plug	Sensor
1	Zone 1	0	1	0	0
	Zone 2	4	1	1	0
	Zone 3	0	1	1	0
	Zone 4	0	1	1	0
2	Zone 1	1	1	1	3
	Zone 2	14	1	1	3
	Zone 3	0	1	1	3
	Zone 4	1	1	1	3
3	Zone 1	4	1	1	3
	Zone 2	1	1	1	3
	Zone 3	0	1	1	0
	Zone 4	1	1	1	3
	Zone 5	1	1	1	3
4	Zone 1	4	1	1	3
	Zone 2	1	1	1	3
	Zone 3	0	1	1	0
	Zone 4	1	1	1	3
	Zone 5	1	1	1	3
5	Zone 1	4	1	1	3
	Zone 2	1	1	1	3

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	Zone 3	0	1	1	0
	Zone 4	1	1	1	3
	Zone 5	1	1	1	3
6	Zone 1	1	1	1	3
	Zone 2	1	1	1	3
	Zone 3	0	1	1	0
	Zone 4	4	1	1	3
	Zone 5	1	1	1	3
7	Zone 1	4	1	1	3
	Zone 2	1	1	1	3
	Zone 3	0	1	1	0
	Zone 4	1	1	1	3
	Zone 5	1	1	1	3
	All zones	55	33	32	72

3.5. *Differences among solutions*

The genetic algorithm can find many solutions with the same objective value. How each solution differ from other solution? The Levenshtein distance from the first solution have been computed. The corresponding histogram is shown in Figure 6. The mean value is 6.12 and maximum value is 13. When Levenshtein distance of a solution is 13, the amount of differences between the the solution and the first one is 13, which is 17,6% of total length. In practice, the Levenshtein distance can be calculated from the initial phases of those devices. These results can be used to estimate the number of switching transfer required to implement a solution.

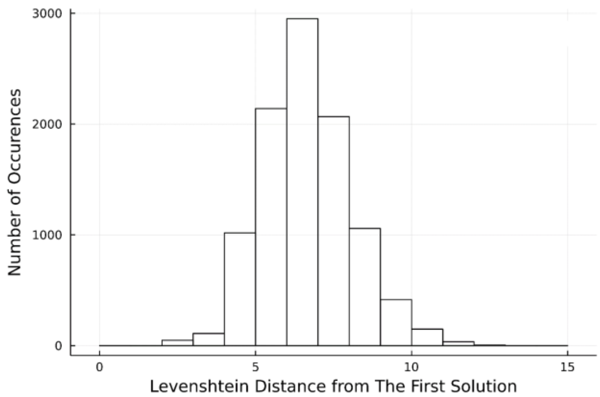

Figure 6 Number of occurrence of Levenshtein distance from the first solution.

3.6. *Computational burden*

The computation times required by given by MILP solver and the proposed method for Case 1a and Case 1b are given in Table 8, Table 9, Table 10, respectively. In general, MIP solver is faster than the proposed method. However, the proposed method requires only few seconds. Hence, the proposed method is fast for many practical applications.

The number of optimal solutions by given by MILP solver and the proposed method for Case 1a and Case 1b are given in Table 8, Table 9, Table 10, respectively. On one hand, the MIP solver always give single solution. On the other hand, the proposed method gives multiple solutions. As number of

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appliances is increased, the number of solutions is also increased at higher rate. Note that similar trend is shown in Table 3.

Table 8 Computational results related to Case 1a

Case 1(synthetic)			
Method	Proposed Method	MIP	Random Assignment
Number of appliances	6	6	6
Unbalance Index	0	0	>=0
Computation time (seconds)	0.39 (mean), 0.21 (std)	0.0074	Not available
Number of Solutions	6	1	0

Table 9 Computational results related to Case 1b

Case 1(synthetic)			
Method	Proposed Method	MIP	Random Assignment
Number of appliances	9	9	9
Unbalance Index	37.5	37.5	>=0
Computation time (seconds)	1.23 (mean), 0.12 (std)	0.18	Not available
Number of Solutions	282	1	0

Table 10 Computational results related to Case 2.

Case 2 (real building in Germany)			
Method	Proposed Method	MIP	Random Assignment
Number of appliances	74	74	74
Unbalance Index	0.015 (mean), 0 (std)	0,015	>0,015
Computation time (seconds)	3.34 (mean), 0.06 (std)	0.3	Not available
Number of Solutions	1000* (mean), 0 (std)	1	0

*Table 1 shows that population size is 1000.

4. DISCUSSION

The genetic algorithm exhibits efficacy in identifying multiple optimal solutions for phase balancing due to several factors. Firstly, as depicted in Figure 6, Levenshtein distances between solutions are relatively low, indicating a high degree of similarity among them. Secondly, the mutation and crossover operations are conducted in incremental steps, modifying only a limited number of genes. Thirdly, the non-numeric string coding closely resembles the DNA encoding upon which the genetic algorithm is based. This alignment between the problem and the method enhances their compatibility.

Previous works in control of appliances in buildings, such as [12], [19], [20], [29], focus on peak load shaving but do not consider phase balancing. On the other hand, there are previous works consider phase balancing using GA such as [23]. However, paper [23] uses utility point of view. The GA in [23] uses integer encoding and does not used to consider multiple global optima. Hence, the proposed method is unique due to its' customer point of view and consideration of multiple global optima.

The proposed method can be used in future scenarios. The concept of smart sustainable buildings describe in [18] envisions phase balancing as an ancillary service. The proposed method can be used in such ancillary service. In another work [8], the unbalance is considered at network level and homes are offered to adjust their consumption accordingly. Hence, there is no balancing effort inside the corresponding homes. Similarly, the proposed method is also relevant in an incentive market discussed [17] which encourage three-phase building participation in phase balancing. Hence, the proposed method can be applied in smart building management system, demand response and energy conservation

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in building. For example, In future demand response program, a building may be expected to consumed unbalanced power [18]. In this regard, the objective function may be modified in into equation where P_{target}^{ϕ} represents targeted power consumption at phase ϕ. With little modification, the proposed method can be used to solve the optimization problem with the new objective function.

$$f(x) = \sum_{\phi=r}^{s}\left(P_{tot}^{\phi} - P_{target}^{\phi}\right)^2 \tag{13}$$

Several limitations exist in the current study. Firstly, the proposed method relies on static loads, while load behavior is random. Incorporating real-time data from smart meters into the phase balancing optimization phase is recommended. Secondly, the study doesn't investigate the impact of renewable energy sources in buildings. Lastly, the method doesn't exhaustively search all global optima, making it intriguing to explore potential solutions using diverse approaches like constraint satisfaction programming.

5. CONCLUSION

This study proposes a string-encoded genetic algorithm for optimizing the phase selection of single-phase appliances in buildings, thereby addressing the issue of phase imbalance in low-voltage networks. The proposed method efficiently identifies multiple optimal solutions, thereby providing flexibility for building energy management. Simulation results demonstrate the method's efficacy in various scenarios, including simple cases, two-story buildings, and multi-story complexes. This approach holds significant relevance for smart building systems and demand response programs, contributing to the field of energy informatics. Future research may explore adaptive optimization techniques and the integration of real-time load data for dynamic phase balancing.

APPENDIX

In order to compare those solutions with each other, a metric named Levenshtein Distance is used [31]. The metric is total number of substitutions, insertions and deletion needed to change one string into another one. If we have two string *a* and *b* (of length |*a*| and |*b*|), the Levenshtein Distance *Le*(*a,b*) is calculated using

$$L(a,b)=\begin{cases} |a|, & if\ |b| = 0 \\ |b|, & if\ |a| = 0 \\ L(\tau(a),\tau(b)), & if\ a[1]=b[1] \\ 1+\begin{cases} L(\tau(a),b) \\ L(a,\tau(b)) \\ L(\tau(a),\tau(b)) \end{cases}, & otherwise \end{cases}$$

The function $\tau(s)$ gives all but the first element of a string *s*.

CONFLICT OF INTEREST

The authors declares that there is no conflict of interest between the authors or with research object in this paper.

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