OPTIMIZATION OF PRELIMINARY GROUNDING SYSTEM DESIGN FOR AC SUBSTATION USING MODIFIED EVOLUTIONARY PARTICLE SWARM OPTIMIZATION

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ABSTRACT

Grounding grid ensures a reliable operation of substation and provides protection to personnel and equipment under faulty condition. In this work, a preliminary grounding system for AC substation is designed based on certain requirements according to the IEEE standard. A modified stochastic optimization technique, known as modified evolutionary particle swarm optimization (MEPSO), was used to optimize the preliminary design of grounding system of an AC substation. The variables were the number of rods, length of the rods, number of parallel columns and number of parallel rows. Comparison of the optimization results between MEPSO and PSO was made to identify a better preliminary grounding design for AC substation. From the results, it was found that MEPSO yields a better optimized design than PSO, which has lower total cost and grid resistance compared to PSO.

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ABSTRAK

Grid pembumian memastikan pencawang elektrik mempunyai operasi yang boleh diharapkan. Ia memberi perlindungan kepada kakitangan dan peralatan pada masa yang kritikal. Dalam penulisan ini, reka bentuk awal grid pembumian untuk pencawang telah direka berasaskan keperluan tertentu dalam piawaian IEEE. Teknik pengoptimuman stokastik yang diubahsuai dikenali sebagai modified evolutionary particle swarm optimization (MEPSO) digunakan untuk mengoptimumkan reka bentuk awal grid pembumian. Pembolehubah untuk pengoptimuman ini adalah bilangan rod, panjang rod, bilangan lajur selari dan bilangan baris selari. Perbandingan keputusan pengoptimuman antara MEPSO dan PSO dibuat untuk mengenal pasti reka bentuk awal yang lebih baik untuk pencawang AC. Dari keputusan penulisan ini, didapati MEPSO menghasilkan reka bentuk awal yang lebih baik daripada PSO dimana MEPSO mempunyai grid rintangan dan kos yang lebih rendah berbanding PSO.

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LIST OF SYMBOLS

c_1	Cognitive Acceleration Factor
c_2	Social Acceleration Factor
c_3	Time Varying Acceleration Coefficient
c_{1i}	Initial Values of Cognitive Coefficient
c_{1f}	Final Values of Cognitive Coefficient
c_{2i}	Initial Values of Social Coefficient
c_{2f}	Final Values of Social Coefficient
C_p	Correction factor
d	Cross-sectional diameter of a grid conductor
D	Average spacing between parallel grid conductors
D_f	Decrement factor for the entire duration of fault
$\mathrm{E_{touch}}$	Tolerable Touch Voltage
E_{step}	Tolerable Step Voltage
E_m	Mesh Voltage/Touch Voltage
E_s	Step Voltage
f	System frequency (Hz)
h	Depth of Grounding Grid
h_s	Thickness of Surface Layer Material

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$iter$	Number of Iteration
$iter_{max}$	Maximum Number of Iteration
I_f	Fault Current
I_g	Maximum Grid Current/Fault Current
K_h	Weighting factor for depth burial
K_i	Corrective factor
K_{ii}	Weighting factor for earth electrodes/ rods on the corner mesh
K_s	Spacing factor
L_c	Total length of horizontal grid conductors in meter
L_M	Effective buried length of conductors
L_R	Total length of earthing rod
L_g	Length of grid
L_x	Maximum length of the grid in x directions
L_y	Maximum length of the grid in y direction
L_s	Effective buried length of conductors
n	Geometric factor
n_r	Number of parallel rows
n_c	Number of parallel columns
p	Soil Resistivity

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p_s	Surface Layer Resistivity
P_c	Crossover Probability
P_m	Mutation Probability
$present[i]$	Current Position of Particle at Current Iteration
Q	Quantization Vector
Q_T	Transpose of Q
$rand$	Equally distributed random number from 0 to 1
R_g	Ground Resistance/Earthing Grid Resistance
S_f	Current division factor
t_f	Fault Duration
t_s	Shock duration
T_a	DC offset time constant in s
$v\ [i]$	Velocity of Particle at Current Iteration
V_{touc}	Tolerable Touch Voltage
V_{step}	Tolerable Step Voltage
w	Inertia Weight
W_g	Width of grid
W_{max}	Upper Limit of Inertia Weight
W_{min}	Lower Limit of Inertia Weight

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LIST OF ABBREVIATIONS

A	Area
GA	Genetic Algorithm
GAO	Genetic Algorithm Optimization
GPR	Ground Potential Rise
Gbest	Global Best
MEPSO	Modified Evolutionary Particle Swarm Optimization
Pbest	Personal Best
PSO	Particle Swarm Optimization
PW	Person Weight
rbest	Neighbor’s Best

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Chapter 1

INTRODUCTION

1.1 Introduction

In this era, the demand on electricity has been increasing to cater both industrial and domestic needs. As a result, more substations are being built to satisfy the needs of electricity (X. Wu, Q.Z. Zhang & J.H. He, 2016). In a substation, grounding grid has a major role, which determines the safety of the substation (Z. Q. He, X.S. Wen & J. W. Wang, 2007). Grounding grid also ensures a reliable operation of substation and provides protection to personnel and equipment under faulty condition (X. Wu, Q.Z. Zhang & J. H. He, 2016).

Cost saving is to be considered when designing and constructing a grounding grid X. Wu, Q.Z. Zhang & J. H. He, 2016). In this study, the aim is to minimize the final costing of grounding grid by minimizing the number of conductors required. Although the number of required conductor is minimized, the maximum touch potential safety criteria is not violated (C. C. Mauricio, L. P. F. Maria, M. Yves, L. C. Jean, & R. C. Jose, 2003).

In order to achieve desired result, modified evolutionary particle swarm optimization (MEPSO) is proposed for grounding grid design, which yields the lowest cost and grid resistance. MEPSO was modified from particle swarm optimization (PSO), which is one of commonly used stochastic search algorithm. The usage of PSO has been increasing due to its ability to solve complex and tough problems (Z. Q. He, X. S. Wen & J. W. Wang, 2007). The results from PSO and MEPSO were compared to determine which optimization method yields lower cost and grid resistance.

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1.2 Problem Statement

For AC substations, it is essential to have a well-designed grounding system. Grounding system is used to divert electric current to ground under abnormal condition. The advantage of having a good grounding system is where the over-voltage magnitudes can be reduced, improves of system and equipment fault protection, reduce in maintenance time and expenses, greater safety for working personnel and reduce of number of faults. Preliminary grounding system is usually designed by proposing a design, which meets the grounding safety criteria without considering the total cost of the design. If the cost of design is considered, trial and error concept is usually used as long as the requirements are met. However, this method is time consuming. Therefore, a new method to minimize the cost of grounding design while the requirements are still met is proposed in this work, which uses optimization method.

1.3 Objectives

The objectives of this study are:

1. To design a preliminary grounding system for AC substation
2. To optimize the preliminary grounding system using MEPSO and PSO techniques
3. To compare between the results obtained using PSO and MEPSO in order to determine which algorithm yields lower cost and grid resistance.

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1.4 Scope of Works

This study is carried out by designing a preliminary grounding system for an AC substation. Matlab software is used for the coding of grounding design. The preliminary grounding system is then optimized by using particle swarm optimization (PSO) techniques to obtain the lowest cost and grid resistance. The PSO simulation is repeated for 10 times, where the results are recorded and compared.

The PSO coding is then modified and becomes modified evolutionary particle swarm optimization (MEPSO). MEPSO simulation is repeated for 10 times, where the results are recorded and compared. The results from PSO and MEPSO are compared to determine which optimization method yields lower cost and grid resistance.

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CHAPTER 2

AC SUBSTATION GROUNDING SYSTEM DESIGN

2.1 Introduction

Grounding grid has a major role in ensuring a smooth substation operation (K. Ishak, A. Syamsir, F. Nur, 2017). Fault current has to be completely directed into the ground to avoid damaging the equipment in the substation and affecting the operation of substation (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014). Grounding grid provides a reference so that the electric potential does not damage the equipment (F. B. Cui, P. Jing, B. Ping, J.B. Guo, J. Y. Song, Y. X. Chen, 2014). Besides, grounding grid protects people around the substation from electric shock hazard (K. Ishak, A. Syamsir, F. Nur, 2017). In this chapter, grounding grid terminology, safety grounding design factor, grounding grid design steps and review of other optimization technique are explained.

2.2 Grounding System

The grounding system performance is determined by few terminologies, which are ground grid resistance, ground potential rise, touch voltages, step voltages etc. The terminologies are defined as following:

A. Ground Potential Rise (GPR)

    GPR is the maximum potential of a grounding grid attain relative to a grounding point assumed to be at the potential of remote earth (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014).

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The equation of GPR is define a following:

$$GPR = I_g * R_g \tag{1}$$

where I_g is the maximum grid current and R_g is the ground grid resistance (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014).

B. Tolerable Touch Voltage

Touch voltage is defined as potential difference between GPR and the surface where the individual is standing while having contact with his/her hands having to grounded structure. The equation of touch voltage is defined as

$$E_{touch} = \frac{(1000 + 1.5. C_s. p)}{\sqrt{t_s}} \tag{2}$$

where C_s is surface layer derating factor, p is the soil resistivity and t_s is the fault current duration (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014).

C. Tolerable Step Voltage

Step voltage is defined as the potential difference felt by the person with a distance of 1m between feet without having connection with grounded structure (M. U Aslam, M. U Cheema, M. B Cheema, M. Samran, 2014). The step voltage is affected by the soil resistivity around the substation. Uniform soil have lower step voltage due to lower soil resistivity. On the other hand, high soil resistivity will have a higher step voltage (G. Y. Liang, 2010). The equation of step voltage is defined as

$$E_{step} = \frac{(1000 + 6. C_s. p)}{\sqrt{t_s}} \tag{3}$$

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D. Fault Current

Maximum current flowing along the grounding grid is known as the fault current. Usually worst type of fault with highest fault current is taken into the design of grounding grid (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014).

E. Mesh Voltage

Mesh voltage is defined as the potential difference of grounding grid and the grounded structure (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014). The equation of mesh voltage is defined as:

$$E_m = \frac{p.K_m.K_i.I_g}{L_m} \qquad (4)$$

where K_m is the geometrical spacing factor, K_i is the corrective factor and L_m is the effective buried length of conductors (H. Dhari, A. M. Alimi, F. Karray, 2008).

F. Step Voltage

Step voltage is defined as the maximum allowable voltage felt by the person calculated by

$$E_s = \frac{p.K_s.K_i.I_g}{L_s} \qquad (5)$$

where K_s is the spacing factor and L_S is the effective buried length of conductors (H. Dhari, A. M. Alimi, F. Karray, 2008).

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G. Grounding Grid Resistance

The grounding grid resistance is the resistance where the fault will flow through and effectively dissipated to the ground. A low grounding grid resistance value is preferable to dissipate fault current to ground without raising the grid potentials (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014).

The equation of grounding grid resistance is defined as:

$$R_g = p[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)] \tag{6}$$

where R_g is the grounding grid resistance, A is the area of grounding grid, L_T is the total buried length of conductors and h is the depth of the grounding grid (A. M. Hassan, E. N. Abdallah & N. H. Abbasy, 2012).

H. Person's Weight

During design stage of a grounding grid, a person weight is one of the important factor that determine the safety of grounding grid. A different weight has a different values of tolerable touch voltage and tolerable step voltage. Typically, the calculation is done based on a person having a weight of 50 kg or 70 kg (M. U. Aslam, M. U. Cheema, M. B. Cheema, M. Samran, 2014).

The objective of a safe grounding grid is where it can direct excessive current during fault condition into the ground without surpassing the operating limits of equipment and its continuation of services. Besides, grounding grid shall be able to prevent any threat of serious electrical shock occurring to the person within the substation (R. Hoerauf, 2013).

In order to achieve a well-designed grounding grid, IEEE standard 80-2000 provides a design summary of grounding grid design. Figure 2.1 shows the complete flowchart of designing a grounding grid (A. M. Hassan, E. N. Abdallah & N. H. Abbasy, 2012).

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The summary is defined as follows (A. M. Hassan, E. N. Abdallah & N. H. Abbasy, 2012):

1. Estimating the area of substation where grounding is needed. The area can be determined by its length and width of the substation. Soil resistivity measurement is then carried out to determine its resistivity and the soil model needed. Typically, the soil can be uniform soil or two-layered
2. Determine the conductor size, fault clearing time including backup and the earth fault current. Usually, the maximum fault current conducted by the conductor is considered as the earth fault current
3. Determine the tolerable touch voltage, step voltage and shock duration. The shock duration may or may not be equal to the fault clearing time depending on the protection scheme and type of re-closer
4. Estimate the spacing between conductor and the grounding rods location. The estimation shall be based on the maximum grid current and the area of grounding grid. After the estimation, the total effective grounding conductor in the system can be determined
5. Calculate the grounding grid resistance based on the estimated values.
6. Perform short circuit analysis to determine the fault current. Only a portion of the fault current that flow to remote earth is considered to prevent overdesign the grounding grid.
7. If the tolerable touch voltage is less than the ground potential rise further analysis is not required. However, if tolerable touch voltage is higher than the ground potential rise, step 8 is required.
8. Calculate the mesh voltage and step voltages.
9. If mesh voltage is higher than tolerable touch voltage, the grounding design need to be revised (Step 11). Otherwise, compare the step voltage and tolerable step voltage.
10. If the step voltage is higher than the tolerable step voltage, grounding design need to be revised (Step 11). Otherwise, the design is safe where no modification required.

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11. Revised the grounding grid design by revising the spacing between conductors, increased the total effective buried conductor by increasing the number of conductor and grounding.

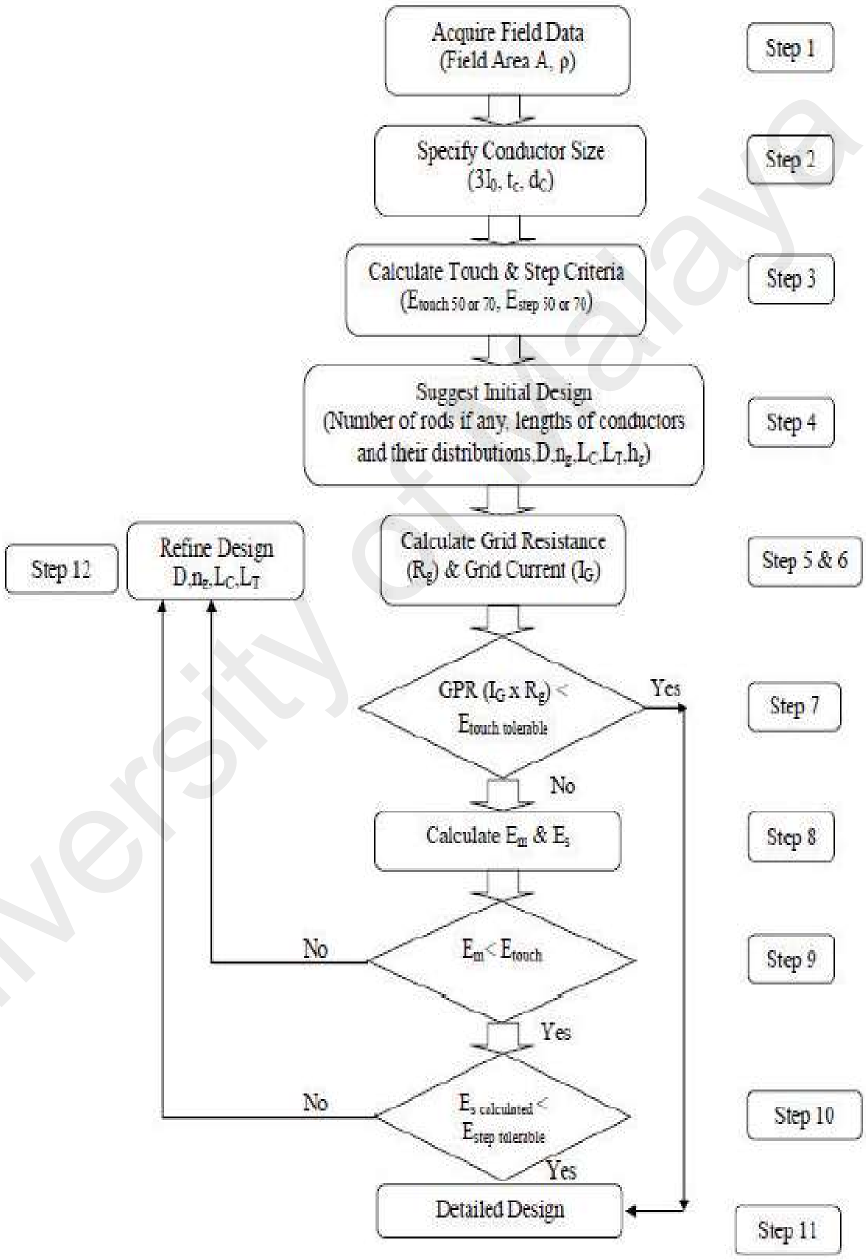

Figure 2.1: Design Flowchart of Grounding System

2.3 Genetic Algorithm Optimization (GAO)

In 1975, John Holland first introduced genetic algorithm. GA performs searching from the whole population which enable discrete, discontinuous and non-convex problem to be solved (M. Zaman, G. H. Fang, X. F. Huang, X. Shuo & W. Xin, 2014). Three technological process is employed by GA which is selection, reproduction, crossover and mutation (B. Alik, Y. Kemari, N. Bendekkiche, M. Teguar & A. Mekhaldi, 2015).

The main objective of GA is to determine the individual who is extremely fit from the whole population. The number of extremely fit individual can be one or more (B. Alik, M. Teguar & A. Mekhaldi, 2015). The lowly fit individuals will be eliminated from the population and retaining only the fit individuals in new population [3]. Evaluation will be continued until the desire termination result is achieve. The flowchart of GA is represented in Figure 2.2 (M. Zaman, G. H. Fang, X. F. Huang, X. Shuo & W. Xin, 2014).

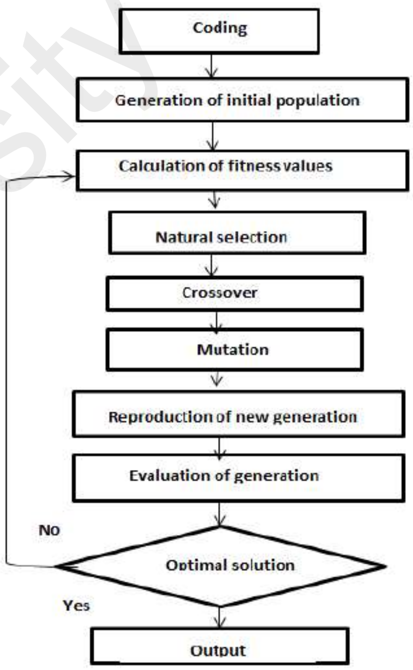

Figure 2.2: Flowchart of Genetic Algorithm

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Genetic algorithm optimization starts by defining the variables to be optimized, the cost function of the problem and ended by analyzing the convergence. The process of genetic algorithm is summarized as following (B. Alik, M. Teguar & A. Mekhaldi, 2015):

I. Cost Function and Variables Selection

Input variables is used where the output will be generated by the cost function. The correct value to be used as input variable is determined by modifying the output in some desired way. At the beginning, an array of variable to optimized known as chromosome is defined. Chromosome has a N_{var} variable given by $x_1, x_2, \dots \dots \dots x_{N_{var}}$. In this study, the variables is defined as $N_x, N_y, d_c, h, N_r, L_r, d_r, h_s$. The chromosome is make up by N_{var} element row vector is defined as following (B. Alik, M. Teguar & A. Mekhaldi, 2015):

$$chromosome = N_x, N_y, d_c, h, N_r, L_r, d_r, h_s \quad (7)$$

From each of the chromosome, the cost function is defined as follows:

$$cost = f(chromosome) = f([N_x, N_y, d_c, h, N_r, L_r, d_r, h_s]) \quad (8)$$

II. Population

The population of GA begins with N_{pop} chromosomes. The final matrix is $N_{pop} x\, N_{bits} x N_{var}$ sized matrix consisting chromosome. Each chromosome has several genes where 0 or 1 is used to represent each of the genes. The population is defined as follows (B. Alik, M. Teguar & A. Mekhaldi, 2015):

$$pop = \begin{pmatrix} chrom1 \\ \vdots \\ chromN_{pop} \end{pmatrix} = \begin{pmatrix} \overrightarrow{1111001001} & & \overrightarrow{1111001001} \\ gene_1 & \dots\dots\dots & gene_{N_{var}} \\ \vdots & & \vdots \\ \overrightarrow{1111001001} & & \overrightarrow{1111001001} \\ gene_1 & \dots\dots\dots & gene_{N_{var}} \end{pmatrix} \quad (9)$$

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III. Variable Encoding and Decoding

A string of binary N_{gene} bits is used to represent the values of variables in binary genetic algorithm. Encoding and decoding is normally used to change the continuous value to binary and mutually. The nth variable x_n binary encoding is defined as follows (B. Alik, M. Teguar & A. Mekhaldi, 2015):

$$x_{norm} = \frac{x_n - x_{lo}}{x_{hi} - x_{lo}} \quad (10)$$

$$gene\ [m] = round\left\{ x_{norm} - 2^{-m} - \sum_{p=1}^{m-1} gene\ [p]2^{-p} \right\} \quad (11)$$

The nth variable x_n binary decoding is defined as follows (B. Alik, M. Teguar & A. Mekhaldi, 2015):

$$X_{quant} = \sum_{m=1}^{N_{gene}} gene\ [m]2^{-m} + 2^{-(m+1)} \quad (12)$$

$$q_n = X_{quant}\ (X_{hi} - X_{lo}) + X_{lo} \quad (13)$$

where x_{norm} is the normalized variable from $0 \leq x_{norm} \leq 1$, x_{lo} is the variable with the lowest value, x_{hi} is the variable with the highest value, gene is the binary version of x_n in terms of meter, x_{quant} is the quantized version of x_{norm}, q_n is the quantized version of x_n and N_{gene} is used to represent the length of the binary string (B. Alik, M. Teguar & A. Mekhaldi, 2015).

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By multiplying both of the vector containing bit and quantified levels, the quantized value of gene or variable can be accurately determined. The equation is defined as follows (B. Alik, M. Teguar & A. Mekhaldi, 2015):

$$q_n = gen * Q^T \tag{14}$$

where Q is the quantization vector $(2^{-1}, 2^{-2}, \dots \dots 2^{-N_{gen}})$ and the transpose of Q is represented by Q_T (B. Alik, M. Teguar & A. Mekhaldi, 2015).

Genetic algorithm is evolving by binary encoding. Decoding must be performed to each chromosome in order to determine the cost. The cost value can be determined when the continuous variable obtained from decoding the cost function is being replaced (B. Alik, M. Teguar & A. Mekhaldi, 2015).

IV. Fitness Function

The fitness of chromosome is determined by a fitness value (B. Alik, M. Teguar & A. Mekhaldi, 2015). The lower the cost value will result in higher fitness values (B. Alik, Y. Kemari, N. Bendekkiche, M. Teguar & A. Mekhaldi, 2015).

V. Mating or Crossover

An arbitrary number with a range of 0 to 1 is generated by genetic algorithm. Crossover probability (P_c) is defined as the threshold where the crossover will occurs. If the arbitrary number is less than than P_C, two random selected chromosome will interchange their genes located after the crossover point (B. Alik, M. Teguar & A. Mekhaldi, 2015).

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VI. Mutation

In genetic algorithm, mutation is the third operation. GA focuses the search of local optimum if the chromosome is alike. The diversity of chromosome is increased by the mutation operator by expanding the searching space in order to determine the global minimum. The chromosome gene will change from 0 to 1 and vice versa. Mutation probability (P_m) is defined as the threshold where the mutation will occurs. The mutation will only occurs if and only if the arbitrary number ranging from 0 to 1 is smaller than P_m (B. Alik, M. Teguar & A. Mekhaldi, 2015).

2.3.1 Review of Grounding System Optimization Using GAO

Genetic Algorithm is widely applied to optimize a grounding system design. Two different studies have been conducted to which GA is used as an optimization tool. Both of the studies has the same objective, which is to reduce the cost of grounding system while maintaining the safety criteria The first study is conducted on Ain El Melh substation. The data obtain regarding on the substation is as follows (B. Alik, Y. Kemari, N. Bendekkiche, M. Teguar & A. Mekhaldi, 2015):

- Area, A = 160m x 160m
- Soil resistivity, p = 50.89 Ω/ m
- Surface layer resistivity, p_s = 3000 Ω. m
- Fault duration, t_f = 0.5 s
- Fault current, I_g = 18.9 kA

A population size of 100 is used in this optimization. Figure 2.3 shows the cost curves as the function of iteration numbers. From Figure 2.3, the grounding system cost is inversely proportional to number of iteration.

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As the number of iteration increases, the cost of grounding system decreases. The optimum cost of $148,047.8 is obtained after 371 times of iterations. The safety parameters and parameter of the final optimum grounding grid design is as shown in Table 2.1 and 2.2. The parameters includes the touch voltage, step voltage, GPR and etc. (B. Alik, Y. Kemari, N. Bendekkiche, M. Teguar & A. Mekhaldi, 2015).

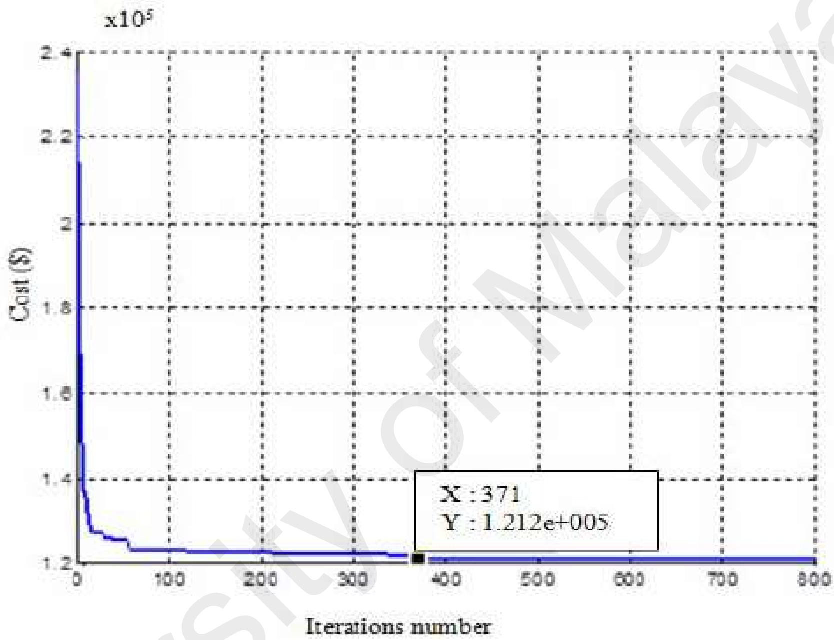

Figure 2.3: Cost Curve of Grounding System

Table 2.1: Safety Parameters of Grounding System Design using GAO

Tolerable touch voltage for human with 70kg body weight, $V_{touch70}$ (V)	457
Tolerable step voltage for human with 70kg body weight, V_{step70} (V)	1480
Tolerable ground resistance, R_g (Ω)	0.15
Grounding potential rise, GPR (V)	2855
Actual touch voltage (V), V_t (V)	418
Actual step voltage (V), V_s (V)	261

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Table 2.2: Design Parameters of Grounding System using GAO

Number of vertical rods, N_r	128
Length of the rod (m)	3
Number of unilateral mesh in the x direction of the substation, N_x	23
Number of unilateral mesh in the y direction of the substation, N_y	7
Total length of the grid conductors (m), L_t	5185
Diameter of grounding rod (mm), d_r	14.08
Surface layer thickness (cm), h_s	8.25
CPU time (s)	24.46
Cost ($)	148,047.8

A second study was conducted on a 220 kV power plant at Labreg. The data obtain regarding the substation is as follows (B. Alik, M. Teguar & A. Mekhaldi, 2015):

- Area, A = 430m x 300m
- Soil resistivity, p_1= 100.67 Ω.m and p_2 = 40.50 Ω. m
- Surface layer resistivity, p_s = 2000 Ω. m
- Fault duration, t_f = 0.5 s
- Fault current, I_g = 14.9 kA

The optimization is carried out with three different size of population which is 30, 90 and 900. The parameters are calculated based on a human with a weight of 70 kg. The safety parameters of grounding grid is tabulated in Table 2.4. The parameters include the GPR, touch voltage, step voltages etc. The resistance of the grounding system is not more than 1Ω. Besides, the actual step voltage is less than the tolerable step voltage which indicates the grounding grid comply with the safety criteria. In Table 2.3, the parameters of the grounding grid such as the number of conductor, length of conductor, costing etc. is tabulated (B. Alik, M. Teguar & A. Mekhaldi, 2015).

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Table 2.3: Optimal Parameters of Grounding System Design using GAO

N_{pop}	**Optimum Parameters**	**GA**
30	N_x	11
	N_y	15
	h (m)	0.8
	hs (m)	0.08
	Lr (m)	4.5
	Nr	4
	dc (m)	0.013
	dr (m)	0.01
	Cost ($)	1245305
90	N_x	15
	N_y	11
	h (m)	0.6
	hs (m)	0.08
	Lr (m)	4
	Nr	6
	dc (m)	0.013
	dr (m)	0.011
	Cost ($)	1239818
900	N_x	15
	N_y	11
	h (m)	0.58
	hs (m)	0.07
	Lr (m)	3.5
	Nr	3
	dc (m)	0.013
	dr (m)	0.012
	Cost ($)	1238435

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.Table 2.4: Safety Parameters of Grounding System Design using GAO

N_{pop}	**Safety Parameters**	**GA**
30	R_g (Ω)	0.076
	GPR (V)	1148
	Tolerable Touch Voltage (V)	660
	Tolerable Step Voltage (V)	1975
	Actual Touch Voltage (V)	450
	Actual Step Voltage (V)	70
90	R_g (Ω)	0.077
	GPR (V)	1159
	Tolerable Touch Voltage (V)	660
	Tolerable Step Voltage (V)	1957
	Actual Touch Voltage (V)	660
	Actual Step Voltage (V)	88
900	R_g (Ω)	0.075
	GPR (V)	1149
	Tolerable Touch Voltage (V)	640
	Tolerable Step Voltage (V)	1896
	Actual Touch Voltage (V)	400
	Actual Step Voltage (V)	91

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2.4 Review of Grounding System Optimization Using PSO

Benamrane Alik, Madjid Teguar, and Abdelouahab Mekhaldi conducted the study on PSO using the same substation data. The optimization result using PSO is tabulated in Table 2.5 and 2.6 respectively (B. Alik, M. Teguar & A. Mekhaldi, 2015).

Table 2.5: Safety Parameters of Grounding System Design using PSO

N_{pop}	**Safety Parameters**	**GA**
30	R_g (Ω)	0.077
	GPR (V)	1159
	Tolerable Touch Voltage (V)	755
	Tolerable Step Voltage (V)	2356
	Actual Touch Voltage (V)	450
	Actual Step Voltage (V)	70
90	R_g (Ω)	0.078
	GPR (V)	1160
	Tolerable Touch Voltage (V)	660
	Tolerable Step Voltage (V)	1957
	Actual Touch Voltage (V)	409
	Actual Step Voltage (V)	68
900	R_g (Ω)	0.078
	GPR (V)	1160
	Tolerable Touch Voltage (V)	691
	Tolerable Step Voltage (V)	2100
	Actual Touch Voltage (V)	420
	Actual Step Voltage (V)	78

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Table 2.6: Optimal Parameters of Grounding System Design using PSO

N_{pop}	**Optimum Parameters**	**GA**
30	N_x	10
	N_y	13
	h (m)	0.8
	hs (m)	0.17
	Lr (m)	5
	Nr	13
	dc (m)	0.012
	dr (m)	0.011
	Cost ($)	1588223
90	N_x	14
	N_y	10
	h (m)	0.8
	hs (m)	0.08
	Lr (m)	5
	Nr	8
	dc (m)	0.013
	dr (m)	0.012
	Cost ($)	1256289
900	N_x	14
	N_y	10
	h (m)	0.7
	hs (m)	0.1
	Lr (m)	5
	Nr	4
	dc (m)	0.012
	dr (m)	0.012
	Cost ($)	1255410

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From the above literature review, Table 2.7 provides a summary on the similar studies that had been carried previously. From Table 2.7, we are able to see that two similar study had been carried out on two different substation. Both of the previous study has the same objective of optimizing the grounding design of the substation by using different type of optimization technique and determine the minimum cost to achieve a safe grounding design.

Table 2.7: Summary of Previously Conducted Studies

Title of Study	**Authors**	**Year of Publication**
Optimization of Grounding System of 60 30 kV Substation of Ain El Melh using GAO	B. Alik, Y.Kemari, N. Bendekkiche, M. Teguar, A. Mekhaldi	2015
Minimization of Grounding System Cost Using PSO, GAO and HPSGAO Techniques	Benamrane Alik, Madjid Teguar, and Abdelouahab Mekhaldi	2015

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CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

In this chapter, the method used for this study is discussed. Section 3.2 provides the details and the assumptions made during the preliminary design of the grounding grid. These assumptions are important in determining the safety parameters of the grounding grid. Sections 3.3 and 3.4 discuss the optimization algorithms used for this study, are particle swarm optimization (PSO) and modified evolutionary particle swarm optimization (MEPSO). MEPSO is modification and improvement from the original PSO.

3.2 AC Substation Grounding System Design

In this study, the preliminary grounding system is designed by making assumptions for few parameters. These parameters mimic as if the study is performed on a real existing 132 kV substation. The assumed parameters are as follows:

- Soil resistivity, p = 300 Ω.m
- Thickness of surface layer material, $h_s = 0.1$
- Shock duration, $t_s = 0.15$ s
- Area , A = 450 m^2
- Depth of grounding grid, h = 0.6 m
- Fault duration, t_f = 0.15 s

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- Maximum single phase to ground fault, $I_f = 3.1$ kA

The preliminary grounding system design calculation is performed using MATLAB software. From chapter 2, a person weight will affect the tolerable touch and step voltages. The tolerable touch and step voltage are determined based on the person weight. The cost for the grounding system is assumed to be directly proportional to the total length of buried conductors including grounding rods. The grounding grid resistance is determined using equation (6) with total buried length of 956 with an area of $450m^2$. Before determining the mesh voltage and step voltage using equation (4) and (5), the grid current is determined as following:

A. Grid Current, I_g

Grid current is the earth fault current that would flow via the grounding system and back to remote earth. The equation are defined as following:

$$I_G = S_f \ x \ I_g \qquad (15)$$
$$= D_f \ x \ S_f \ x \ I_f$$

where S_f is the current division factor, D_f is the decrement factor for the entire fault duration and I_f is the fault current. In this study, a single phase to earth fault is assumed to occur. The decrement factor can be determined by following equation:

$$D_f = \sqrt{1 + \frac{T_a}{t_f}\left(1 - e^{\frac{-2t_f}{T_a}}\right)} \qquad (16)$$

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Each of the term in equation is defined as follows:

- T_a = dc offset time constant in $s = (X/R)(\frac{1}{2\pi f})$
- t_f = fault duration
- $\frac{X}{R}$ = ratio at the fault location
- f = frequency of the system in Hertz

As the system capacity increases, the maximum expected fault current will increase as well. In order to cater higher fault current, a correction factor C_p is applied to equation (14). Therefore equation (14) can be rewrote as following:

$$I_G = D_f \ x \ S_f \ x \ I_f \ x \ C_p \tag{17}$$

C_p is a factor which accounts the increase of fault current due to growth of the system. Usually C_p is set with a minimum value of 1.2 to a maximum value of 1.5. In this study, the value of each term is tabulated as following:

Table 3.1: Value of Each Term Used to Determine Grid Current

Term	**Values**
S_f	0.6
I_f	3.1 kA
t_f	0.5s
$\frac{X}{R}$	15
f	50 Hz
C_p	1.2

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After determine the I_G from equation (16), ground potential rise is determined by using equation (2). With the same value of grid current, mesh voltage is determined using equation (4). The geometrical spacing factor, K_m and irregularity factor, K_i in equation (4) is determined by following equation:

$$K_m = \frac{1}{2*\pi}\left[\ln\frac{D^2}{16*h*d} + \frac{(D+2*h)^2}{8*D*d} - \frac{h}{4*d}\right] + \frac{K_{ii}}{K_h} * \left[\ln\frac{8}{\pi(2*n-1)}\right] \quad (18)$$

Each of the term in equation is defined as follows:

- D = average spacing between parallel grid conductors
- h = conductor buried depth
- d = conductor cross-sectional diameter
- K_h = weighting factor for depth burial = $\sqrt{(1+h)}$
- K_{ii} = weighting factor for earth electrodes/ rods on the corner mesh

The average spacing between parallel grid conductors is determined by following equation:

$$D = \frac{1}{2} * \left(\frac{W_g}{n_r - 1} + \frac{L_g}{n_c - 1}\right) \quad (19)$$

where W_g is the width of the grid and L_g is the length of grid, n_r is the number of parallel and n_c is the number of columns. The value for conductor cross-sectional diamter, width of grid, length of grid, number of parallel rows and number of parallel columns is 0.01236 m, 50m, 90m, 6 and 7 respectively. The value of K_{ii} will be equal to 1 as the grounding system is assumed to have earth electrodes along the grid.

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As we assume the grounding system is having earth electrode along the grid, the effective buried length of conductors, L_M is determined by following equation:

$$L_M = L_C + \left[1.55 + 1.22 \left(\frac{L_r}{\sqrt{{L_x}^2 + {L_y}^2}} \right) \right] * L_R \tag{20}$$

Each of the term in equation is defined as follows:

- L_x = maximum length of the grid in x directions
- L_y = maximum length of the grid in y direction
- L_c= total length for horizontal grid conductors in meter
- L_R = total length of earthing rod

After determine the mesh voltage, the grounding system design is continued by determining the step voltage. The step voltage is determined by equation (5). The spacing factor K_s, corrective factor K_i, and the effective buried length of conductors, L_s is determined by following equation:

$$K_s = \frac{1}{\pi} * \left[\frac{1}{2 * h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] \tag{21}$$

$$K_i = 0.644 + 0.148 * n \tag{22}$$

$$L_s = 0.75 * L_c + 0.85 * L_R \tag{23}$$

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Each of the term in equation (20) and (21) is defined as follows:

- D = average spacing between parallel grid conductors
- h = grid conductor buried depth
- n = geometric factor

The geometric factor is determined by following equation:

$$n = n_a \, x \, n_b \, x \, n_c \, x \, n_d \tag{24}$$

where each term n_a, n_b, n_c, n_d is further determined by following equation:

$$n_a = \frac{2 * L_C}{L_p} \tag{25}$$

$$n_b = \sqrt{\frac{L_p}{4 * \sqrt{A}}} \tag{26}$$

$$n_c = \left(\frac{L_x * L_y}{A}\right)^{\frac{0.7 * A}{L_x * L_y}} \tag{27}$$

$$n_d = \frac{D_m}{\sqrt{{L_x}^2 + {L_y}^2}} \tag{28}$$

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By using equation (20) to equation (27), we are able to determine the step voltage of the preliminary grounding system. Both of the mesh and step voltage is then compared to tolerable value to determine whether if the grounding system has met the safety criteria. If the safety criteria is not met, preliminary design modification is performed where variables such as spacing between parallel conductor, geometric factor, etc. is adjusted.

3.3 Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is one of the population-based meta-heuristic algorithm (A. Starkey, H. Hagras, S. Shakya, G. Owusu, 2016). In 1995, Rusell Eberhart and James Kennedy invented PSO based on the inspiration from flocking birds or schooling patterns of fish (H. Lotfi & A. Dadpour, 2017). PSO is able to solve multidimensional, complex constrained and nonlinear problems (K. Salah, 2017). PSO is advantageous to work area optimization problem as is solve problems using real numbers (A. Starkey, H. Hagras, S. Shakya, G. Owusu, 2016).

Each and every solution is termed as "birds" in the search space where its call as particle (K. Salah, 2017). The whole population is called as swarm (A. Starkey, H. Hagras, S. Shakya, G. Owusu, 2016). Each particle can be the solution to the optimization problem. These particles will determine the best position in the search space by two factor, which is the previous best position and the best position among the swarm (H. Lotfi & A. Dadpour, 2017). PSO algorithm begins by initializing the swarm with random solutions (A. Starkey, H. Hagras, S. Shakya, G. Owusu, 2016). Each particle will be updated by two values in each iteration. The first value is known as Pbest. It is the best value the particle has obtained after each iteration. The second value is known as the Gbest. It is the best value the population or the swarm has obtained so far (K. Salah, 2017). The best value is the leader where the leader will be the guidance to other particle to reach a better solution in the search space (A. Starkey, H. Hagras, S. Shakya, G. Owusu, 2016).

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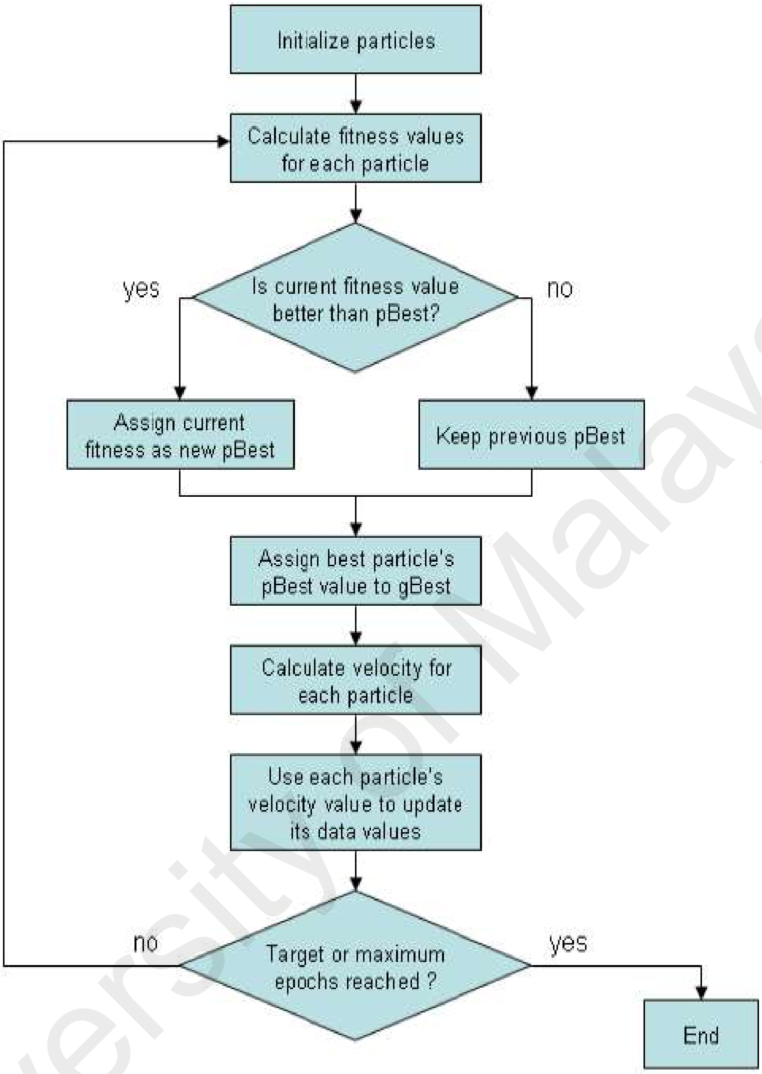

Figure 3.1: Flowchart of PSO Algorithm

Figure 3.1 shows the process of PSO (K. Salah, 2017). The process of PSO starts by initializing the particles set by the user. In each iteration, the fitness of the particle is determined and compared with Pbest. If the current fitness value of the particle is better that the current Pbest, the value of Pbest will be replaced by the value of the current fitness else it is neglected.

From the Pbest achieve by each particle, the best value among the particle is chosen to be the Gbest. After determine the Gbest, the velocity of each particle will be calculated. The velocity of each particle is then used to update the data values of the particle. The process of the PSO will continued until the maximum epoch or iteration is reached.

In PSO, each particle from each iteration will have a velocity value. It is a value that determines how far the particle is from the target value. The distance of the particle from the targeted result and velocity value is directly proportional. The further the distance of the particle from target result, the bigger the velocity value.

The following equation is used to update the velocity of each particle (K. Salah, 2017):

$$v\,[i] = w * v[i] + \ c_1 * rand * (Pbest\,[i] - present\,[i]) + c_2 * rand * (Gbest[i] - present[i]) \tag{29}$$

$$present[i+1] = present[i] + v[i] \tag{30}$$

Each of the term in equation is defined as follows (K. Salah, 2017):

- $v\,[i]$ = velocity of particle at current iteration
- $present[i]$ = current positions of the particle at current iteration
- $rand$ = equally distributed random number from 0 to 1
- c_1 = cognitive acceleration factor
- c_2 = social acceleration factor
- w = inertia weight

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The inertia weight is usually set during learning and reduces linearly.The values of inertia weight can be determined by [9]

$$w = W_{max} - \frac{W_{max} - W_{min}}{iter_{max}} * iter \tag{31}$$

where $iter$ is the present iterations number, $iter_{max}$ is the maximum number of iteration, W_{max} is the upper limit of inertia weight and W_{min} is the lower limit of inertia weight (H. Lotfi & A. Dadpour, 2017).

In this study, the grounding code and PSO are combined together to optimize the grounding system design. A total of four solutions is to be determined using PSO, where each solution is determined with four different swarms. Each of the swarm has a total of 40 particles where the initial velocity is set to zeros. The solutions to be determined are length of earthing rod, number of row conductor, number of column conductor and number of earthing rod. These parameters are limited by two boundaries, namely as upper bound and lower bound. Upper bound is set to 10 where the lower bound is set to 3. The reason for this boundaries is to have a limitation for each of the parameters. The maximum number of iteration in this PSO is set to 20. The inertia weight upper limit and the lower limit are 0.9 and 0.4 respectively. Lastly, both cognitive and social acceleration factor is set to 0.7.

3.4 Modified Evolutionary Particle Swarm Optimization (MEPSO)

In MEPSO, a few parameter of the algorithm such as number of iterations, number of particles, upper bound and lower bound remains unchanged. "rbest" is introduced in the velocity equation. The new velocity equation is as follows:

$$v\,[i] = w * v[i] + c_1 * rand * (Pbest[i] - present[i]) + \; c_2 * rand * (Gbest[i] - present[i]) + \; c_3 * rand * (rbest[i] - present[i]) \tag{32}$$

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The new term rbest is the neighbor's best values which is randomly selected from the Pbest achieved by another particle as shown in Figure 3.2. By modifying the velocity equation, each particle has extra information, which enhances the searching behavior and improves the particle's exploration in the search space.

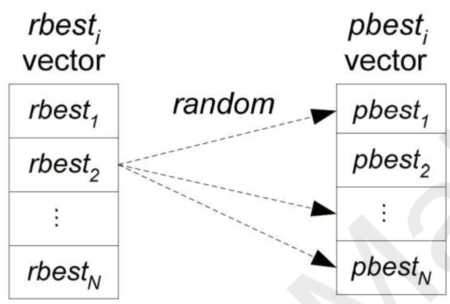

Figure 3.2: Determination of *rbest*

In MEPSO, c_1 *and* c_2 are calculated instead of setting it to a constant value of 0.7. From equation (17), c_3 is known as the time varying acceleration coefficient, which pulls the particle near to $rbest$. c_1, c_2 *and* c_3 are determined by following equations:

$$c_1 = c_{1i} + (c_{1f} - c_{1i}) \times \frac{iter}{iter_{max}} \tag{33}$$

$$c_2 = c_{2i} + (c_{2f} - c_{2i}) \times \frac{iter}{iter_{max}} \tag{34}$$

$$c_3 = c_1 \times (1 - \exp(-c_2 \times iter)) \tag{35}$$

c_{1i} and c_{1f} are initial values and final values of cognitive coefficient respectively while c_{2i} and c_{2f} are initial values and final values of social coefficient respectively. c_1 *and* c_2 should be different with the number of iteration in order to enhance the exploration and exploitation of each particle.

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If c_1 has a large value and c_2 has a small value in initial iteration, the particles will be pushed to move around the entire search space. As the number of iteration increases, values of c_1 will decreases and the values c_2 will increases and finally the particles will be pulled to the global solution. c_{1i} and c_{1f} are set as 2 and 0.2 respectively while c_{2i} and c_{2f} are set as 0.2 and 2 respectively.

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CHAPTER 4

RESULTS OF GROUNDING SYSTEM DESIGN OPTIMIZATION

4.1 Introduction

In this chapter, the result of this study is explained and discussed. For this study, the results are focused on the number of row conductor, number of column conductor, and number of earthing rod, the length of each rod and the total cost of grounding system. In order to indicate that the grounding system is safe, the safety parameters of the grounding system is provided. Section 4.2 shows the results of a preliminary AC substation grounding system design. Section 4.3 shows the results of the grounding system after optimization. Section 4.4 shows the results of grounding system using modified optimization algorithm. In section 4.5, both of the results from PSO and MEPSO are compared to determine which algorithm is able to give better optimized grounding design. In section 4.6, both of the result of MEPSO and past work is compared.

4.2 Preliminary AC Substation Grounding System Design

The preliminary AC substation grounding system is designed by trial and error. The designed parameter is tabulated in Table 4.1.

Table 4.1: Preliminary Grounding System Design Parameters

Number of Row Conductor	6 nos.
Number of Column Conductor	7 nos.
Number of Earthing Rod	22 nos.
Length of Earthing Rods	3 m

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Table 4.2: Safety Parameters of Preliminary Grounding Design

Parameters	**Results**
Tolerable Touch Voltage, V_{touch}	1.72 kV
Tolerable Step Voltage, V_{step}	5.66 kV
Touch Voltage, E_m	1.24 kV
Step Voltage, E_s	5.35 kV
Earthing Grid Resistance, R_g	2.3 Ω
Ground Potential Rise, GPR	5.89 kV
Total length of grounding conductor	956

By using the design parameters and the assumptions made in section 3.2, the safety parameters as tabulated in Table 4.2 can be achieved. The current industrial standard specify that the grounding grid is consider safe if the touch voltage and the step voltage is less than tolerable touch voltage and tolerable step voltage. The data shows that both touch voltage and step voltage are less than the tolerable touch voltage and step voltage respectively. From the result, the preliminary grounding design is safe since the safety criteria is met.

The total length of buried conductor is 890 meter and the total length of earthing rod is 66 meter. As mentioned in section 3.2, the cost is assumed to be directly proportional to the total length of conductor. The costing is considered high, where cost saving requirement cannot be fulfil. In order to solve the costing problem, the preliminary design is optimized using optimization methods.

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4.3 Grounding Design Optimization using PSO

In PSO optimization, the number of row conductor, column conductor, earthing rod and length of rod are determined by the algorithm instead of trial and error. The results of grounding design optimization using PSO are tabulated in Table 4.3 and Table 4.4. Table 4.3 consists of the first 5 simulation results while Table 4.4 consists of the 6th to 10th simulation result. The safety parameters of the grounding design after optimization is recorded on the 10th simulation and is tabulated in Table 4.5. Figure 4.1 shows the convergence characteristic of PSO. It shows that PSO converges to the final solution at 7th iteration.

Table 4.3: Result of optimization using PSO

Number of Simulation	**1st**	**2nd**	**3rd**	**4th**	**5th**
Number of Column (nos)	6	6	5	6	6
Number of Row (nos)	4	4	4	4	4
Number of Earthing Rod (nos)	4	3	9	3	3
Length of Rod (m)	3	5	7	4	4
Total length of grounding conductors (m)	672	675	673	672	672
Grid resistance (Ω)	2.41	2.41	2.40	2.41	2.41

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Table 4.4: Result of Optimization using PSO

Number of Simulation	**6th**	**7th**	**8th**	**9th**	**10th**
Number of Column (nos)	6	6	6	5	6
Number of Row (nos)	4	4	4	4	4
Number of Earthing Rod (nos)	3	4	3	7	4
Length of Rod (m)	4	3	4	9	3
Total length of grounding conductors (m)	672	672	672	673	672
Grid resistance (Ω)	2.41	2.41	2.41	2.41	2.41

Table 4.5: Safety Parameters of Grounding Design using PSO

Parameters	**Results**
Tolerable Touch Voltage, V_{touch}	1.72 kV
Tolerable Step Voltage, V_{step}	5.66 kV
Touch Voltage, E_m	1.71 kV
Step Voltage, E_s	616.7 V
Ground Potential Rise, GPR	6.17 kV
Total length of grounding conductors (m)	672
Grid resistance (Ω)	2.41

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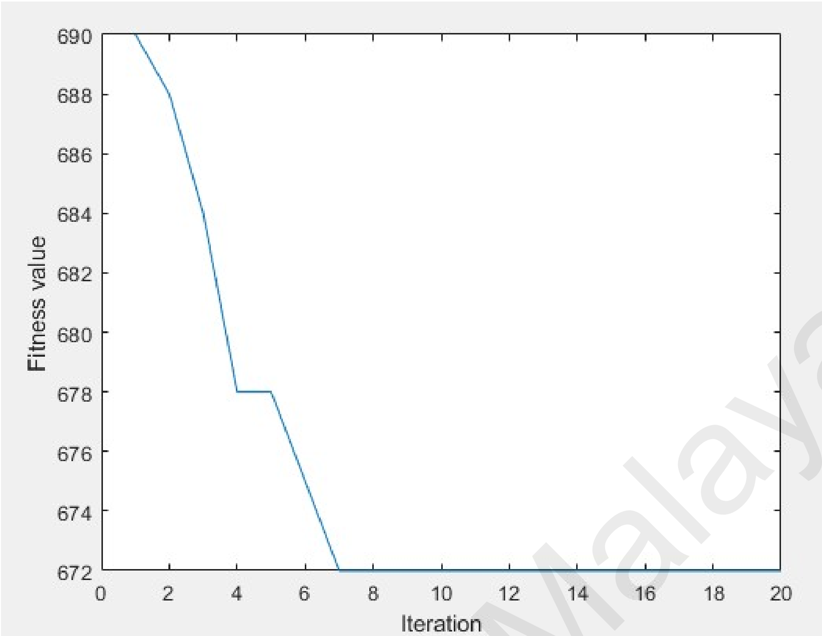

Figure 4.1: Convergence Characteristic of PSO

The grounding design after optimization is considered safe as both of the touch voltage and step voltage are less than the tolerable values. The final number of column conductor, row conductor, earthing rod and length of each rod used is 6, 4, 4 and 3m respectively. By comparing the results with the preliminary grounding grid design, the number of conductors used column has decreased where the most significant reduction is on the number of earthing rod. Although the total number of conductor is reduced, a safe grounding design with a low earthing grid resistance of 2.41 Ω is met.

Besides, the total cost the grounding design has decreased as the total number of conductor decreases. The total length of grounding conductors for the optimized grounding design is 672 m inclusive the earthing rods. By using PSO, the cost is reduced by 30% compared to the cost of preliminary grounding design. The amount of the total cost saving is significant and is crucial to projects where the cost is the main consideration in designing a grounding system.

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4.4 Grounding Design Optimization using MEPSO

A modified evolutionary PSO (MEPSO) is implemented to optimize the preliminary grounding design. The optimization is performed using the settings for PSO. The result of MEPSO is tabulated in Tables 4.6 and 4.7 respectively. Similar to PSO, the safety parameters are recorded on the final simulation and are tabulated in Table 4.8.

Table 4.6: Result of optimization using MEPSO

Number of Simulation	**1st**	**2nd**	**3rd**	**4th**	**5th**
Number of Column (nos)	6	6	5	6	5
Number of Row (Nos)	4	4	4	4	4
Number of Earthing Rod (Nos)	3	4	9	3	9
Length of Rod (m)	4	3	7	4	7
Total length of grounding conductors (m)	672	672	673	672	673
Grid resistance (Ω)	2.33	2.33	2.49	2.37	2.33

Table 4.7: Result of Optimization using MEPSO

Number of Simulation	**6th**	**7th**	**8th**	**9th**	**10th**
Number of Column (nos)	6	5	5	5	6
Number of Row (nos)	4	4	4	4	4
Number of Earthing Rod (nos)	4	9	9	7	3
Length of Rod (m)	3	7	7	9	4
Total length of grounding conductors (m)	672	673	673	673	672
Grid resistance (Ω)	2.35	2.45	2.33	2.41	2.31

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Table 4.8: Safety Parameters of Grounding Design using MEPSO

Parameters	**Results**
Tolerable Touch Voltage, V_{touch}	1.72 kV
Tolerable Step Voltage, V_{step}	5.66 kV
Touch Voltage, E_m	1.36 kV
Step Voltage, E_s	580.11 V
Ground Potential Rise, GPR	5.92 kV
Total length of grounding conductors (m)	672
Grid resistance (Ω)	2.31

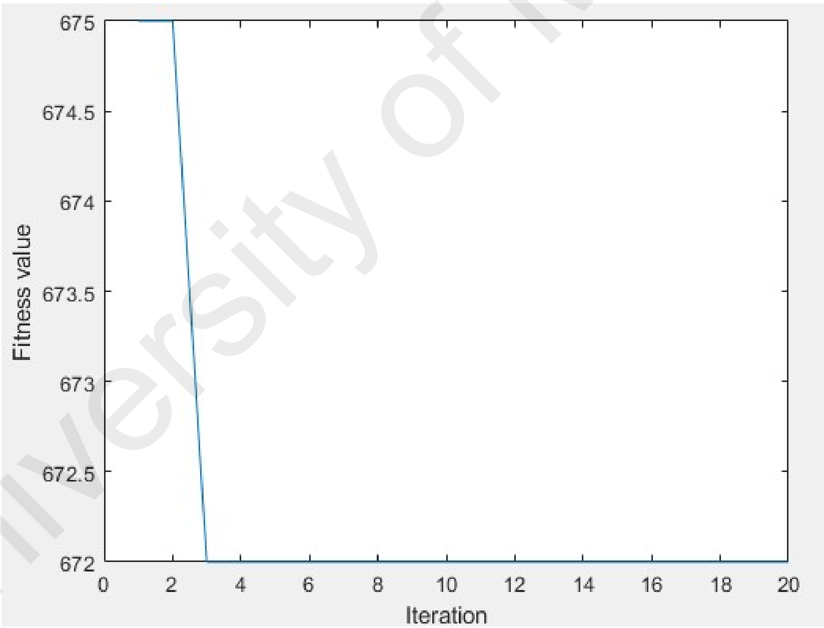

Figure 4.2: Convergence Characteristic of MEPSO

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Form the results in Table 4.6 and Table 4.7, the final number of the column conductor, row conductor and earthing rod length used is 6, 4, 3 and 4 m respectively. The touch voltage and step voltage are 5.66 kV and 1.36 kV respectively. The optimized grounding design using MEPSO is safe as the value of touch voltage and step voltage are lower than the tolerable value. The final total length of grounding conductors and the grounding grid resistance is 672 m and 2.36Ω respectively. Figure 4.2 shows the convergence characteristic of MEPSO. From the characteristic curve, MEPSO converges to the final solution at 3rd iteration.

4.5 Results Comparison between PSO and MEPSO

In this section, both of the results from PSO and MEPSO are compared. The comparison is made based on the number of conductor used, safety parameter, total cost and the earthing grid resistance. The comparison results are tabulated in Table 13.

Table 4.9: Results comparison between PSO and MEPSO

Parameters	Types of Optimization	
	PSO	MEPSO
Number of Column (nos)	6	6
Number of Row (nos)	4	4
Number of Earthing Rod (nos)	4	3
Length of Rod (m)	3	4
Touch Voltage (V)	1.71 kV	1.36 kV
Step Voltage (V)	616.7 V	580.11 V
Grid Resistance (Ω)	2.41 Ω	2.31 Ω
Total length of grounding conductors (m)	672	672

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The number of columns and rows for the grid conductor obtained by both of the algorithms are similar. However, both of the algorithm provides a different number of earthing rod and different length of the grounding rod. MEPSO yields a less number of earthing rod with a longer length of the rod. On the other hand, PSO has the opposite results where the number of earthing rod is higher with shorter length of the rod. With different types of grounding design configuration, MEPSO yields a lower earthing grid resistance than PSO. In this case, a lower earthing grid resistance is more favorable as it will be easier for the fault current to dissipate to ground.

4.6 Results Comparison between MEPSO and Past Work

In this section, MEPSO is used to perform an optimization based on the substation data from previous study conducted by B. Alik, Y. Kemari, N. Bendekkiche, M. Teguar & A. Mekhaldi. The purpose of the comparison is to determine whether MEPSO is able to provide a better optimized design compared to GA. The comparison result is tabulated in Table 4.10.

Table 4.10: Results comparison between GA and MEPSO

Parameters	**Types of Optimization**	
	GA	**MEPSO**
Number of Column (nos)	7	3
Number of Row (nos)	23	3
Number of Earthing Rod (nos)	128	3
Length of Rod (m)	3	3
Touch Voltage (V)	418 V	1.67 kV
Step Voltage (V)	261 V	5.48 kV
Grid Resistance (Ω)	0.15 Ω	0.19 Ω
Total length of grounding conductors (m)	5185	969

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From the comparison, the number for column conductor, row conductor and earthing rod has greatly reduced from 7, 23, 128 to 3, 3, and 3 respectively. The length of rod for both GA and MEPSO remains the same at 3 meter each. Since the number of conductor used is greatly reduced, the total length of grounding conductor also reduces from 5185 meter to 969 meter. This shows that by using MEPSO a lower cost of grounding conductor can be achieved. Although the grid resistance of MEPSO is higher than GA, the result is acceptable as MEPSO has a lower cost with only a 0.04 Ω difference in grid resistance.

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CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In this work, optimization of preliminary grounding design has been successfully performed. Two main algorithms were used in this study, namely particle swarm optimization (PSO) and modified evolutionary PSO (MEPSO). PSO is a conventional algorithm normally used for many optimization problems while MEPSO is the modified version of PSO. The performance of PSO and MEPSO was evaluated based on the total cost of the grounding system and the earthing grid resistance of the final design.

From the results that have been obtained, PSO and MEPSO yield the same total cost of the grounding system. However, with the same amount of total cost between PSO and MEPSO, MEPSO has a better solution with a lower value of earthing grid resistance. Therefore, this shows that MEPSO is able to perform better in optimizing the preliminary grounding design compared to PSO.

5.2 Future Work

Future work that can be performed are as follows:

1. A hybrid algorithm can be proposed, where GA and PSO are combined to perform optimization on the preliminary grounding design. GA and MEPSO can be also be performed.
2. Use more parameters as variables for optimization of grounding grid design.

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