Improving magnetic fields in overhead transmission lines using the insulated cross-arm method

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ABSTRACT

This research study evaluates the effectiveness of the insulated cross-arm (ICA) method in reducing magnetic field (MF) levels in transmission lines. Using Ansys Maxwell finite element method (FEM) software, the study models and analyses the MF distribution in 132 kV and 275 kV overhead transmission lines (OTLs) in Malaysia. The findings reveal that implementing the ICA method can substantially reduce MF levels, improving MF performance by 36% (at 132 kV) and 48% (at 275 kV). These findings have important implications for mitigating potential health risks associated with high MF exposure near transmission lines. Furthermore, the study highlights the potential for future enhancements in ampacity and emphasizes the importance of promoting a health-conscious environment. Field studies, assessments, and investigations into economic feasibility and practical implementation are recommended for further validation and application of the ICA method. Overall, this research study contributes to the knowledge and understanding of reducing MF exposure and improving the efficiency of power transmission systems.

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1. INTRODUCTION

The South and East Asia regions have witnessed significant development in recent years, especially in Malaysia and Pakistan. The rapid growth has led to increased urbanization, as rural areas are transformed to meet the needs of a growing population and achieve national development goals. According to the Malaysian Energy Information Hub (MEIH), electricity consumption in Malaysia has increased by 174% between 2000 and 2021, with a projected 33.8% increase by 2050. This growth is mainly due to the expanding population, which has grown by 43% between 2000 and 2021. The Department of Statistics Malaysia predicts that the population will continue to grow, reaching 40.55 million by 2040, as shown in the graph in Figure 1. However, rapid urbanization has also resulted in converting many rural areas to urban areas to meet the growing demand for housing, infrastructure, and commercial buildings. As a result, power lines have been erected closer to residential areas. This goes against safety protocols, raising concerns about the health risks associated with exposure to electromagnetic fields (EMF) radiated by power lines shown in Figure 2 [1]-[4].

To address this issue, there is a need to find a way to deal with the growing demand for electricity while minimizing health risks from EMF radiation. One possible solution is to modify the design of existing power transmission towers by incorporating insulated cross-arms (ICAs) technology. ICA meets all the safety criteria for installation on existing extra high voltage (EHV) power transmission towers, eliminating the need for standard vertical strings of insulators and allowing for the conductor height to be raised. ICA technology is a potential solution to address this issue, and further research in this area could lead to a safer and more sustainable power transmission system. Conductors position comparison with and without the implementation of ICA for 132 kV overhead transmission line (OTL) as shown in Figure 3.

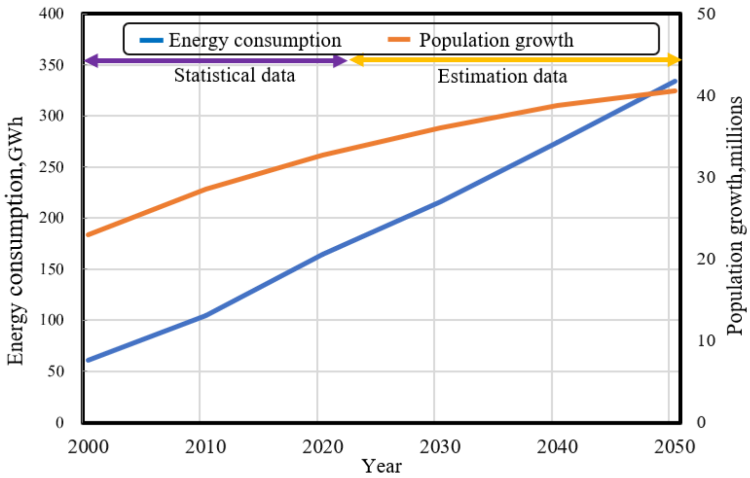


Figure 1. Estimated human population increase and final electricity consumption in Malaysia from 2000 to 2050 [1], [2]

Figure 2. Infringement of a transmission line’s right of way caused by infrastructure growth [3], [4]

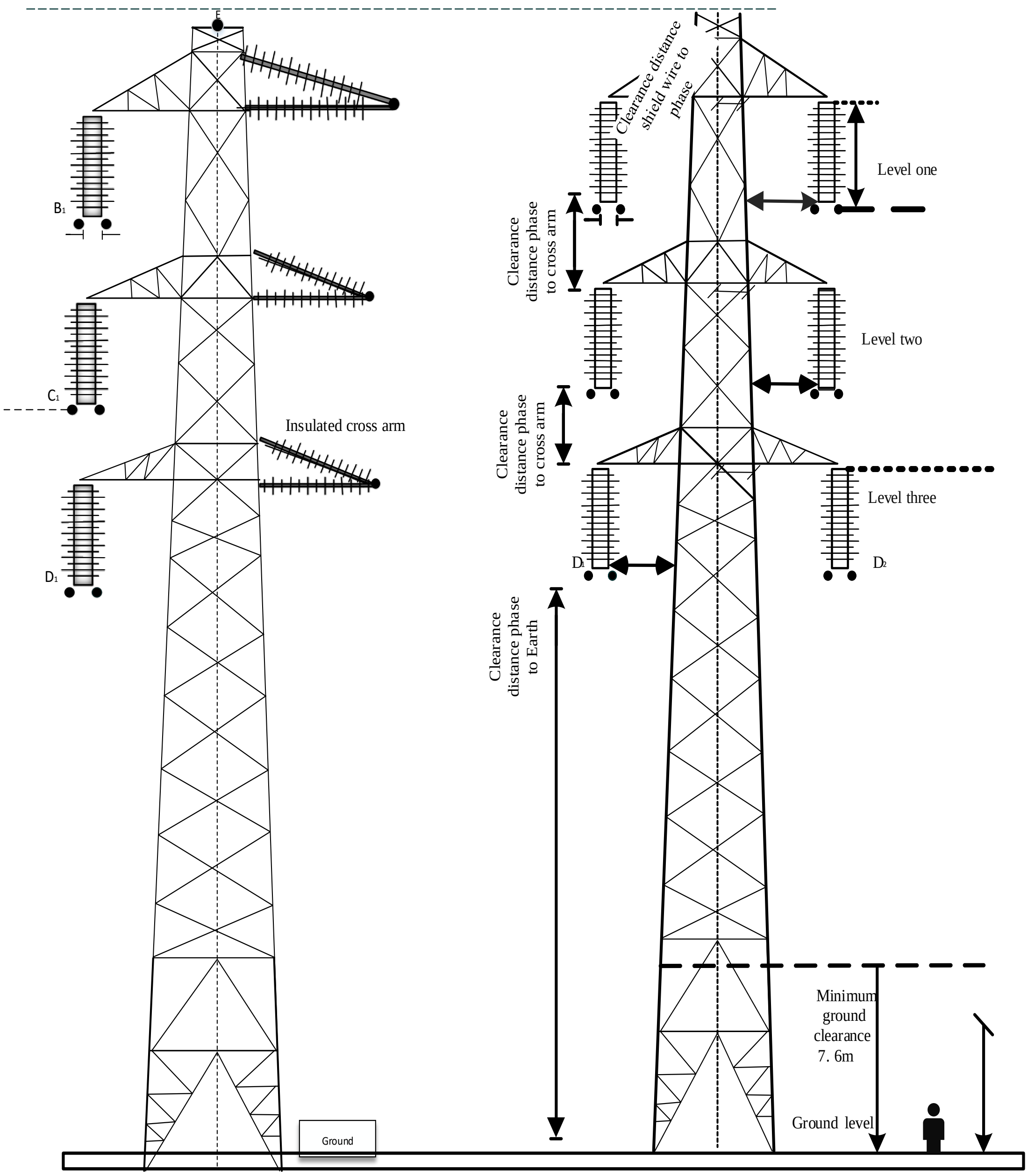


Figure 3. Conductors position comparison with and without the implementation of ICA for 132 kV OTL [3]

2. LITERATURE REVIEW

The overhead lines generate a magnetic field (MF) in their vicinity due to a load current flowing in the conductors. MF intensity is proportional to the current, varying with load conditions. As the current increases, so does the MF. The MF strength decreases when the distance of power lines increases [5] and is measured in Tesla (T) or Gauss (G). Most OTLs are three-phase. Each phase has one or two or more conductors, and the ground-level MF is the sum of all the MFs produced by the currents in all the conductors [6]. MF calculation is one of the factors that should be considered during the design process, especially for high-voltage transmission lines.

High-voltage transmissions began installing ICA in the mid-60s. In the 1970s, Kimoto *et al*. [7] developed a prototype ICA for a 345 kV EHV transmission line. Figure 4 shows Kimoto's version of the twin-arm and quadrant types. These designs don't need extra insulators.

In 1998, Barbarito *et al*. and Cecchetti and Noferi published their work on insulators as cross-arms for a new bi-dimensional steel tower structure. This new tower design is physically compact and reduces right-of-way (ROW), MF level, and tower/foundation costs by up to 10% [8], [9]. Tenaga National Berhad (TNB) Malaysia is applying a technology similar to the fully ICA type to build power transmission lines in newly developed areas, as shown in Figure 5 [10]. However, this technology could only be utilized in newly developed areas and not on the existing lines. In 2014, Rowland *et al*. [11] developed an ICA that can increase lattice tower capacity by 25%. Additionally, this method can be used to build compact towers, such as reducing the height of conventional 400 kV towers. Utilising a modern EMF calculation method, Goffinet *et al*. [12] published a paper highlighting how critical it is to design the end fitting and placement of the grading ring or arcing horn for long-term performance.

In 2021, Qian Wang *et al.* measured the lightning flashover characteristics of a full-scale transmission tower. They concluded that the ICA installation degraded the lightning-withstand and MF levels [13]. Previous researchers have proved the reliability of Ansys Maxwell software in determining the MF radiation level from (OTL) systems [14]. This research observes MF radiation levels from OTL system conductors, with and without implementing the ICA method. The basic Ansys Maxwell simulation design in this research is based on the work published by Vornicu *et al.* [15].

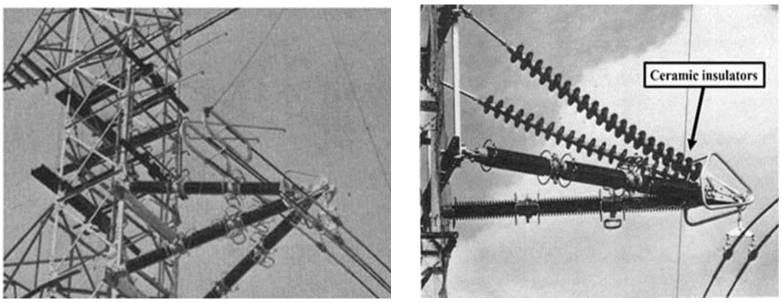


Figure 4. Kimoto's version is a twin ICA type [9]

Figure 5. Front view of a compact tower [8]

3. METHOD

In this research paper, FEA modeling was carried out using ANSYS Maxwell software and based on the following procedures, shown in Figure 6:

- Designing of geometry – geometry designed or imported from other software into ANSYS Maxwell.
- Boundary value conditions – define the properties of the materials utilized in the model. Additionally, the physics requirements must be provided.
- Meshing and refinement – make sure the final solution is independent of the meshing size by splitting the model into many discrete elements.
- Solution and visualization – data extraction, followed by table and figure presentations of the findings.

The general procedure of finite element method (FEM) simulation is shown in Figure 6(a).

3.1. Finite element analysis (FEA)

FEA is a numerical method for solving complex mathematical problems, such as a continuous object with infinite degrees of freedom. FEA modeling aims to reduce the infinite degrees of freedom to finite by segmenting the model into many discrete-sized elements. Several physics research parameters determine how these components will interact. One such is establishing the electrostatics model's voltage potential and dielectric permittivity. Depending on the model design and the number of dimensions, these components are often triangular or quadrilateral in form. A linear or quadratic function may approximate the solution to each model element since the model is split into many simple geometries, Figure 6(b) general procedures of FEM Simulation. The complicated model is solved by assembling a Galerkin matrix for each element and then adding each matrix to create a single matrix [16]-[23].

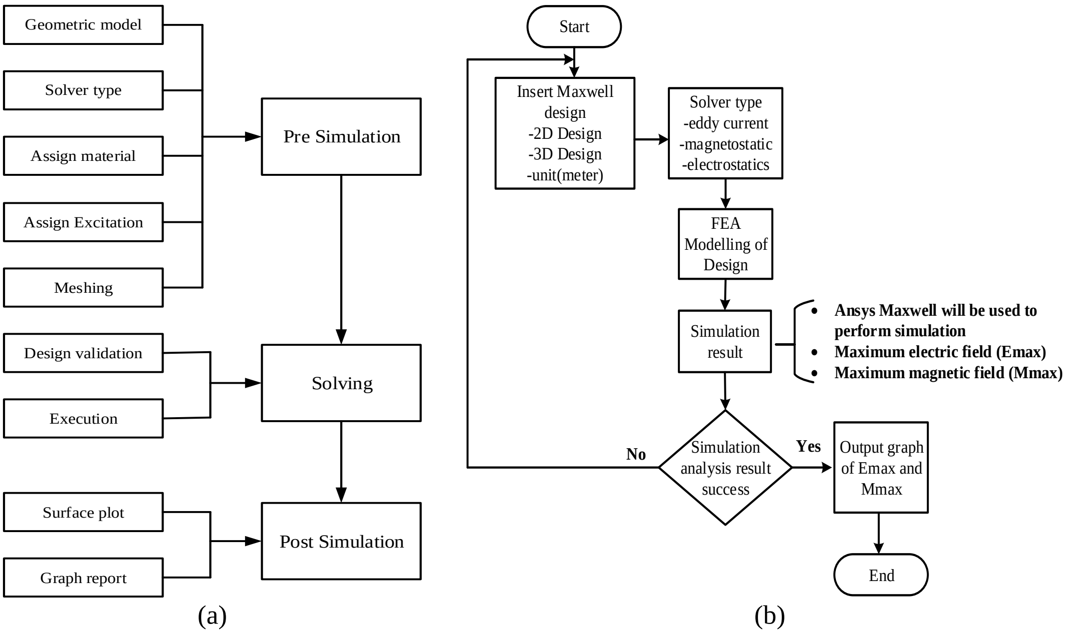


Figure 6. FEA modeling (a) general procedure of FEM simulation and (b) flow chart of FEA

3.2. MF simulation model using Ansys Maxwell software

A simple 2-dimensional (2D) finite element model is used to compute the root-mean-square (RMS) MF flux density generated by a 132 kV double-circuit OTL system using Ansys Maxwell 2D electromagnetic simulation software shown in Figure 7. The only OTL components modelled are the conductors acting as the MF radiation source. Conductors are modelled as single infinite aluminium cylinders with electrical conductivity, σ_c of 3.8×107 S/m, and relative permeability equal to 1. The boundary conditions applied are of a Balloon type, which mimics the space extending to infinity, which consists of the air and soil, which has conductivity, σ_c of zero and 0.05 S/m, respectively, and relative permeability, μ for both equals 1. Table 1 summarizes the parameters used for the Ansys Maxwell 2D simulation model. Parameters are based on the typical conductors used for 132 kV (ACCC) and 275 kV (ACCC) in Malaysia, as presented in Tables 2 and 3. The conductors' ampacity and sag values provided in these tables are given based on the steady-state heat balance equation and parabolic sag equation mathematical calculations at 75 °C of conductor working temperature (CWT) presented in [24].

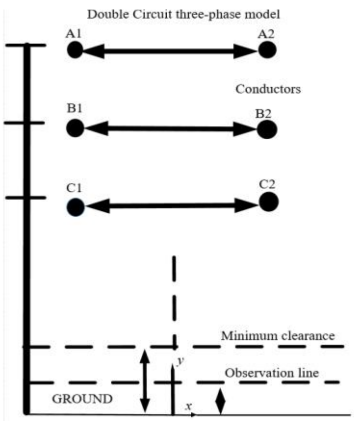


Figure 7. Model of OTL

The 75 °C of CWT is the standard practice for the final temperature parameters in both equations. Additionally, the transposed conductor phase configurations (RYB – B’Y’R’) are considered due to their ability to provide the lowest peak MF level in comparison to the untransposed conductor phase configurations (RYB – R’Y’B’) [25].

The conductors’ positions specified in Tables 2 and 3 are based on Malaysia’s typical 132 kV and 275 kV OTL tower dimensions without implementing ICA. The x-position indicates the conductors’ horizontal distance from the OTL tower midpoint according to the cross-arm length. In comparison, the y-position shows the conductors’ vertical distance according to the cross-arm height subtracted with the sum of insulator length and conductor sag. The conductors’ position in the y-direction is added to implement the ICA method with the insulator lengths. As commonly practiced in MF exposure assessment studies, Figure 8 shows the whole MF simulation design model, distribution of MF level, and instantaneous MF level.

Table 1. Parameters were used for the Ansys Maxwell 2D simulation model

Parameters	Values
Conductors	ACCC
Conductivity	3.8×10^{7} S/m
Permeability	1
Ground	0 V
Conductivity	0.05 S/m
Permeability	1
Width	100 m
Air	1.0006
Conductivity	Null
Permeability	1
Width	100 m
Boundary type	Tangential fields
Air	Balloon
Ground	Balloon
Solution type	Eddy current
Frequency	50 Hz

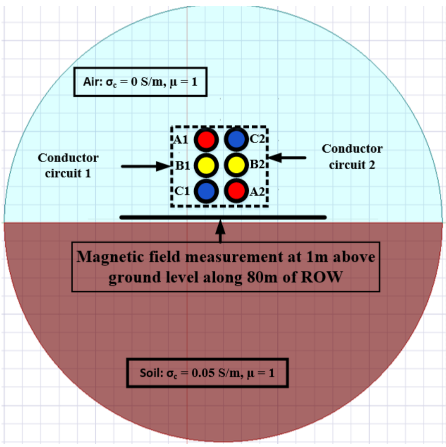
Table 2. The 132 kV OTL system simulation model parameters without ICA implementation

Parameters	Values		
Conductors’			Circuit 1
Position	x	y	Phase
R	- 4.42 m	23.85 m	0°
Y	- 4.42 m	20.15 m	120°
B	- 4.42 m	16.45 m	240°
			Circuit 2
B’	4.42 m	23.85 m	240°
Y’	4.42 m	20.15 m	120°
R’	4.42 m	16.45 m	0°
Type	ACCC		
Current	2111 A		
Sag	8.36 m		
Diameter	24.16 mm		
Insulator length	1.97 m		

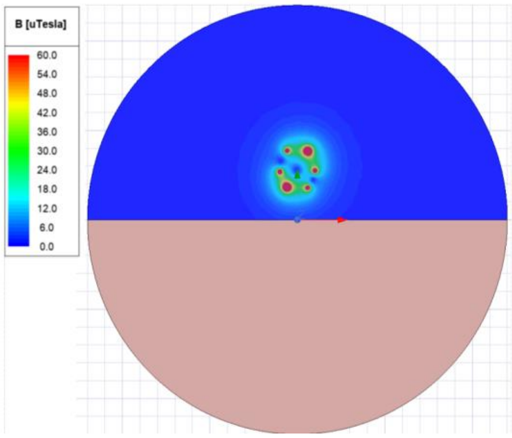
Table 3. The 275 kV OTL system simulation model parameters without ICA implementation

Parameters		Values	
Conductors’		Circuit 1	
Position	x	y	Phase
R	- 6.50 m	30.19 m	0°
Y	- 6.50 m	22.68 m	120°
B	- 6.50 m	15.17 m	240°
		Circuit 2	
B’	6.50 m	30.19 m	240°
Y’	6.50 m	22.68 m	120°
R’	6.50 m	15.17 m	0°
Type	ACCC		
Ampacity	2552 A		
Sag	6.17 m		
Diameter	28.62 mm		
Insulator length	4.17 m		

MF measurements are typically taken 1 m above ground level along 40 m of ROW according to international commission on non-ionizing radiation protection (ICNIRP) guidelines [4] shown in Figure 8(a). As the model is solved using an eddy current solver, which allows the calculation of MF oscillating with 50 Hz of frequency, results are generated in instantaneous magnetic flux density values over a 20 ms period, as shown in Figure 8(b). To obtain the RMS magnetic flux density, these instantaneous magnetic flux density profiles depicted in Figure 8(c) are exported into Microsoft Excel and processed in a point-by-point calculation proposed by Vornicu *et al.* [15].



(a)



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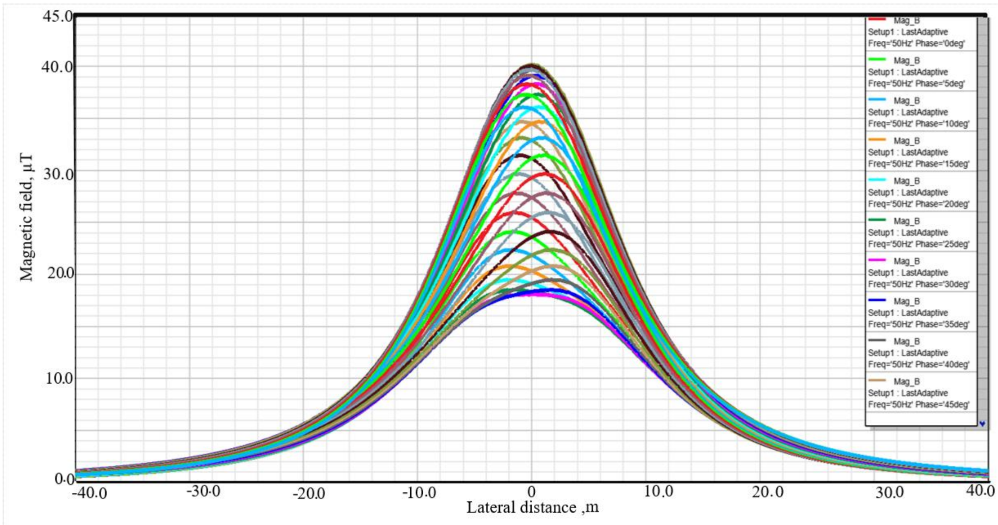

(c)

Figure 8. Ansys Maxwell 2D OTL simulation model: (a) design model, (b) distribution of MF levels, and (c) instantaneous magnetic flux density

4. RESULTS AND DISCUSSION

The MF distribution level from ACCC for the 132 kV (OTL) system at 75 °C of CWT within the span of 40 m ROW at 1 m above ground level is presented in Figure 9. Upon observation, the MF level is the highest at the midpoint between conductors Circuit 1 and Circuit 2. The MF level decreases as the distance from the midpoint increases towards the edge of ROW (further from conductors). Without the implementation of ICA, the highest MF level is recorded at 33 μT (midpoint), with the lowest recorded at 4.29 μT (edge of ROW). With the implementation of ICA, the highest MF level is recorded at 21 μT (midpoint), with the lowest recorded at 3.75 μT (edge of ROW). Based on these numbers, implementing ICA on 132 kV OTL systems reduces MF by up to 36% (midpoint) and 13% (edge of ROW) compared to without ICA.

Similarly, the MF distribution level from ACCC for the 275 kV OTL system at 75 °C of CWT within 40 m ROW at 1 m above ground level behaves in the same manner as presented in Figure 10. In this case, without the implementation of ICA, the highest MF level is recorded at 40 µT (midpoint), with the lowest recorded at 15 µT (edge of ROW). With the implementation of ICA, the highest MF level is recorded at 25 µT (midpoint), with the lowest recorded at 5.0 µT (edge of ROW). These numbers show that implementing ICA on the 275 kV OTL systems allows MF reduction up to 48% (midpoint) and 27% (edge of ROW). The summarization of the MF distribution level for both OTL systems with and without the implementation of ICA is presented in Table 4.

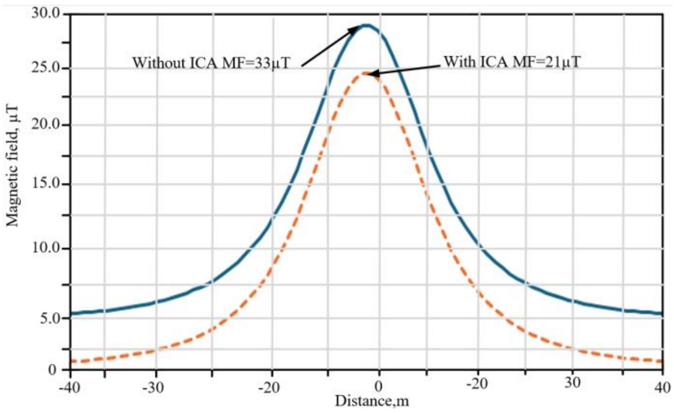

Figure 9. MF underneath 132 kV OTL systems at 1 m above ground level

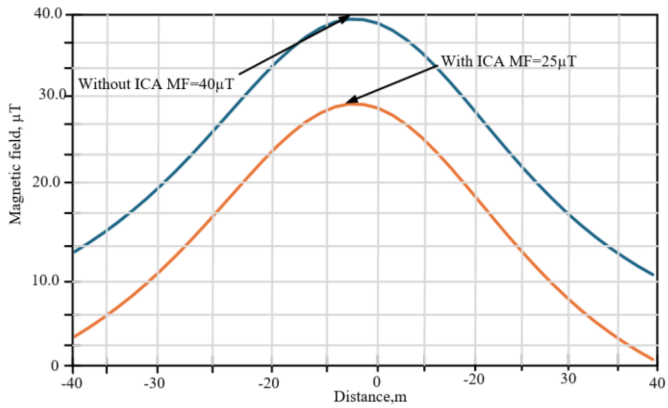

Figure 10. MF underneath 275 kV OTL systems at 1 m above ground level

Table 4. Summarization of MF distribution level for 132 and 275 kV systems with and without ICA implementation

OTL type	Magnetic field, µT			
	Without ICA		With ICA	
	Midpoint	Edge	Midpoint	Edge
132 kV	33	5.0	21	3.0
275 kV	40	15	25	5.0

5. CONCLUSION

The findings of the research indicate that the use of the ICA method appears to be an effective way to reduce the MF radiation at ground level for the existing 132 kV and 275 kV OTL systems in Malaysia. Using Ansys Maxwell simulation software, the study demonstrated that the length of the eliminated insulators directly affects the percentage of MF reduction. The 275 kV OTL system shows a higher MF reduction of up to 48% compared to 36% for the 132 kV OTL system. Implementing the ICA method reduces MF radiation and improves ground clearances, allowing for more ampacity and enhancing the capacity of the OTL systems. The research suggests that the ICA method is a promising solution for reducing MF radiation in existing OTL systems. However, further research is necessary to explore its economic feasibility and long-term effects.

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