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Distribution Network Expansion Planning Considering Massive Penetration of Electric Vehicle Loads

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ABSTRACT

The widespread growth of Distributed Energy Resources (DERs), mainly due to its numerous operational and planning benefits inevitably requires the inclusion of this kind of generation in Distribution Network Expansion Planning (DNEP) models. This chapter addresses the multistage DNEP problem of a distribution network system where massive penetration of Electric Vehicle (EV) loads and integration with DERs are jointly considered. The massive penetration of EV loads has negatively impacted the DNEP, especially on the power losses and voltage stability. Hence, this situation has led to the need for unifying rules for the DNEP to accommodate this additional load. In this research, the optimal DNEP plan identifies the optimal placement and sizing of multiple DERs candidate assets to overcome these issues for medium voltage distribution network. The incorporation of DERs in DNEP drastically increases the complexity of the optimization process. In order to shed light on the modelling difficulties, metaheuristic techniques are adopted in this research. The DNEP, EV loads and DERs are modelled using MATLAB environment. Due to their proven efficacy in earlier studies, the metaheuristic techniques Lightning Search Algorithm (LSA) and Modified Lightning Search Algorithm (MLSA) are employed. The MLSA approach will best minimize power losses and voltage stability at the real-world 69-bus radial distribution network system, according to the simulation's results. The study has demonstrated that placing and sizing variable distributed energy resources (DERs) optimally might lower power loss and increase voltage stability. Moreover, the outcomes show that a combination of DERs might yield a better result than just one DER. Because of the widespread adoption of EVs, it was determined that the numerous DERs in conjunction with the MLSA approach are most suited to be adopted in order to reduce power losses and enhance the voltage profile in DNEP.

Keywords:
Electric vehicle; power loss; distribution network system; metaheuristic technique

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1. Introduction

Paradigm shift in transportation fuel sources to electromobility is expected to have a rapid increase in power demand, hence posing a significant challenge to already overstretched power networks across the globe. According to the forecasts, Electric Vehicles (EVs) are expected to reach 50% of global new car sales by 2035 under current policy settings [1]. This expected increase has warranted immediate action to investigate the impact of EVs on the Distribution Network Expansion Planning (DNEP) and possible solutions to facilitate faster adoption of EVs, preferably without or with minimal distribution network infrastructure upgrades. Numerous studies suggest that the imminent transformation due to EVs and Distributed Energy Resources (DERs) will fundamentally reshape the design and operation power distribution systems, creating new opportunities across various fronts [2]. Up to 2050, Malaysia's total power demand is expected to increase by 2% per year. This increase is accelerated by electrification, reaching 2.6% yearly [3]. As outline in 2021 under Low Carbon Mobility Blueprint (LCMB) 2021-2030, Malaysia is aiming to have 10,000 EVCS in place by 2025 [4]. Hence, in this research, the massive penetration of EVCS into existing distribution network will be focused in order to develop a comprehensive DNEP along the 20 years of planning horizon in Malaysia.

When these EVs connect to the power grid for charging, they are seen by the power system as new loads. In order to handle this increased demand for charging, this circumstance has led to the need for harmonizing regulations or reevaluating the electrical system. Significant issues with the power system output, including worse power quality and increased power loss, are brought on by this massive power demand [4]. Losses may increase, particularly if EV charging stations are installed as standard equipment in every building where mitigating risk becomes essential. Previous studies indicate that the additional EV loads are likely to overwhelm the nearby substation transformer and cable [5]. On the other hand, the mitigation might lessen the strain and buy enough time for the utility to update the network. Furthermore, a number of studies demonstrate that by managing the real power in the distribution system, DERs can reduce power loss [6]. Positive effects of DERs include a decrease in power loss [7], an increase in hosting capacity [7-9], support for management faults [10,11], support for variations in both voltage and frequency [10,12], enhancement of voltage profiles, particularly during peak demand [13] and an increase in the resilience of the power grid [14].

Thus, in order to minimize power loss and maintain voltage stability, this study will employ metaheuristic approaches to take into account the best location and sizing of DERs. Furthermore, a realistic 11kV 69-bus radial distribution network serves as the foundation for the load, EV and distribution network system profiles. Additionally, the usefulness of the metaheuristic methods LSA and MLSA in identifying the most trustworthy result will also be investigated in this study by Nasir *et al.,* [15].

The key novelty in this study arises from the lack of unified methodologies for addressing the simultaneous integration of EV loads and DERs into DNEP. While earlier research has studied the impact of EVs or DERs separately on power systems, few studies have addressed their joint effect on the network, especially in terms of the complexities introduced to the multistage DNEP optimization process. Moreover, the incorporation of variable DERs, which can provide dynamic generation and consumption profiles, significantly complicates the placement and sizing decisions within the distribution network. This gap necessitates an approach that can simultaneously optimize these aspects to improve power loss reduction and voltage stability.

The objective for this research is to develop an optimal DNEP framework that incorporates both EV loads and DERs into the planning process. The specific focus for this research is as the followings:

i. Identifying optimal placement and sizing of DERs to reduce power losses and enhance voltage stability in a medium voltage distribution network.
ii. Overcoming the complexity introduced by the integration of EV loads and DERs in the optimization process using metaheuristic techniques, specifically the LSA and MLSA.
iii. Demonstrating that the integration of multiple DERs rather than a single DER solution can yield superior results in terms of minimizing power losses and improving voltage profiles.

This study bridges the gap in current literature by simultaneously addressing the combined challenges of EV penetration and DER integration in DNEP, offering a novel solution to improve the operational efficiency and reliability of modern distribution networks.

The paper is organized as follows: The modelling of pertinent factors, including power flow, EVs and DERs, is defined in depth in Section 2. This section delineates the comprehensive approach for determining the ideal dimensions and positioning, which relies on the suggested metaheuristic methodologies. Next, concentrate on presenting all of the outcomes of the in-depth research and discussion in section 3.0. In Section 4, the study conclusions are finally provided.

2. Methodology

This section will focus on detailed specifications of EV Loads and DERs. First, the modelling of the DNEP will consider massive penetration of EV loads and normal load growth. Then, DERs will be integrated with DNEP and with the objective function. Finally, the overall results from this research will be discussed.

2.1 Modelling of Distribution Network Expansion Planning (DNEP)

Figure 1 depicts the single line schematic for the realistic 11kV 69-bus radial distribution network [16] system used in this study. This distribution network system is made up of 6 feeders and 69 buses. The primary sources of this distribution network system are from the grid through 132/33kV and 33/11kV distribution transformer. Firstly, the existing distribution is modelled by using PSS/ADEPT software to obtain the preliminary results of power losses and voltage profiles. The existing distribution network system has been forecasted to accommodate normal load growth of 2& yearly as well as massive penetration of EVCS.

In Distribution Network Expansion Planning (DNEP), load Forecasting [17] is important planning research that is used to forecast future power demand or sales growth. Forecasts that are accurate, trustworthy and defendable will assist planners in making sensible investment decisions for system extension, reinforcement and new plant-up to meet rising demand. The horizon of demand forecast could be short, medium or long-term depending on the uses of the forecast. According to the Distribution Code, the prediction horizons for DNEP are as follows: short term (1 - 2 years), medium term (2 - 5 years) and long term (6 - 20 years). According to the Planned Energy Scenario (PES), Malaysia's final energy consumption would double by 2050, with energy demand increasing 2.0% yearly on average [3].

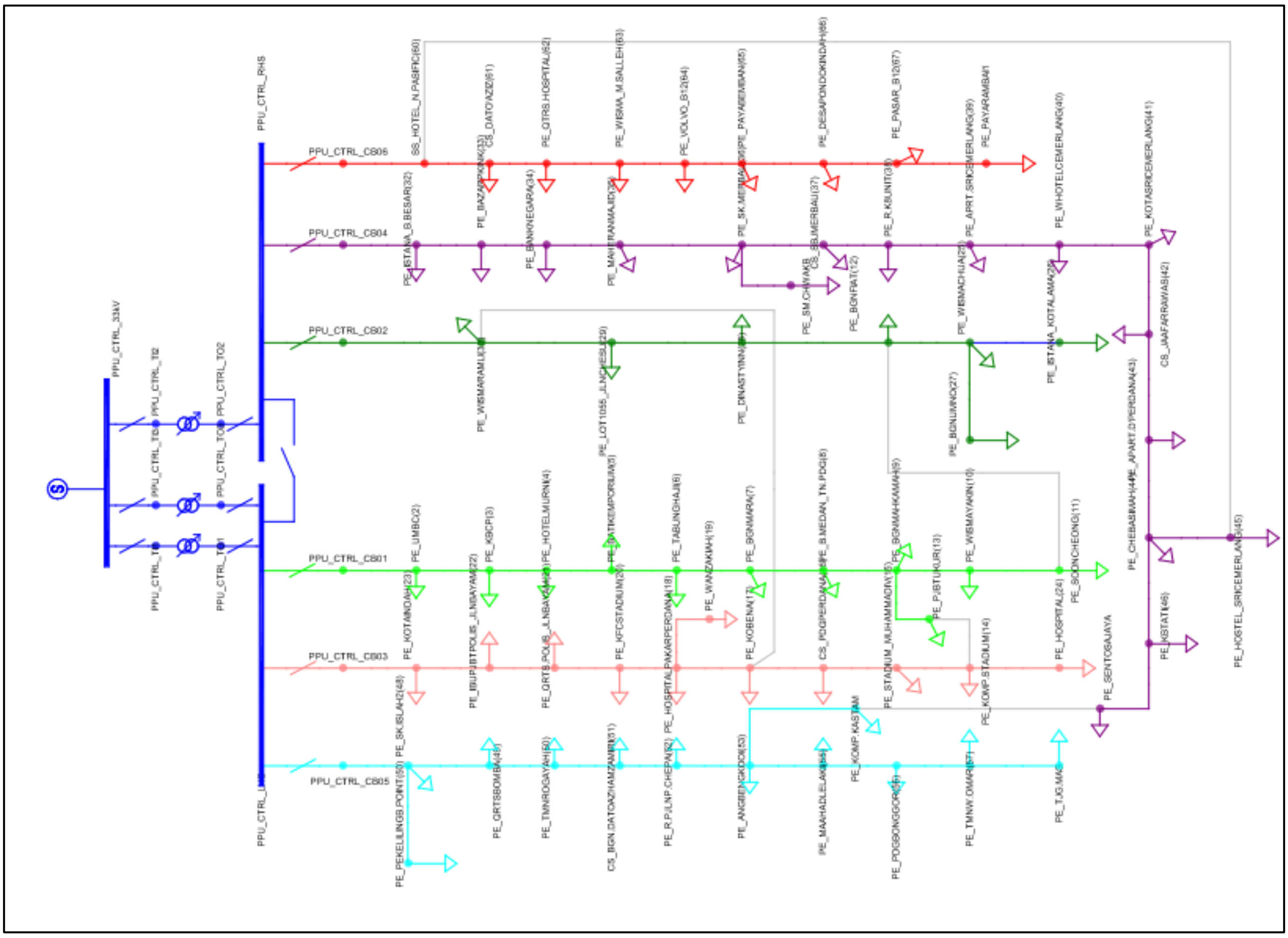

Fig. 1. Single line schematic for the realistic 11kV 69-bus radial distribution network

2.2 Modelling of Electric Vehicle Loads

SAE Standards [19] for charger types will be employed in this research for EVCS modelling. Table 1 details the power for the EV loads that will be used in this investigation. The time it takes to fully charge an EV at level 1 (slow charging) is between 6 and 14 hours. The time required to completely charge the EV at level 2, which is medium charging, is 3 to 4 hours. The time needed to fully charge the EV with level 3 quick charging is between 20 and 30 minutes. Realistic measurements have been used to scale down the injection of EVCS loads into the distribution network to 1 MVA and 11 kV per unit.

Table 1
Details of electric vehicle charging station based on SAE standard

Charger Type	Real Power	Reactive Power
Level 1	1.92 kW	0.60 kVAr
Level 2	19.2 kW	5.99 kVAr
Level 3	120 kW	37.44 kVAr

2.3 Modelling of Distributed Energy Resources (DERs)

Malaysia now prioritizes diversifying its resource base to fulfil growing energy demand while preserving energy security. The nation's total primary energy supply has increased at an average annual rate of 3% over the past ten years, with fossil fuels predominating in the energy mix [18]. The effects of deploying DERs on active and reactive power losses are determined by the quantity of DERs installed and the ratings of the output power pattern [20]. The technology utilized to create the plant, as well as the design of both active and reactive power generation to the distribution system, determine the characteristics of each solar DER. The DERs were modelled to produce either active or reactive electricity based on their technical features. Because this study focuses solely on power loss and voltage profile, all DERs will produce only active power and will be assumed to have a power factor of unity. The placement and sizing of DERs will be determined by the bus's greatest losses and the voltage profile at the bus.

2.4 Objective Functions

Power loss and voltage profile are the two objective functions that are the focus of this research for DNEP purposes [21]. Two buses are connected to a cable or overhead wire in the majority of distribution systems. Eq. (1) and Eq. (2) provide a theoretical representation of the power loss [15].

$$S_{loss} = \sum_{l}^{n} V_{i,l} I_{ij,l}^{*} + V_{j,l} I_{ji,l}^{*} \quad (1)$$

$$P_{loss} = real\ (S_{loss}) \quad (2)$$

Where;
S_{loss} - Apparent power losses
P_{loss} - Real power losses
$V_{i,l}$ - Local voltage at *l*th line
$V_{j,l}$ - Remote voltage at *l*th line
$I_{ij,l}^{*}$ - Current flow from local to remote lth line
$I_{ji,l}^{*}$ - Current flow from remote to local at lth line
n - Total number of lines

The formula given by Imani *et al.,* [22] can be used to determine the voltage profile at each buss. This equation is shown in Eq. (3). The requirement that all bus voltages stay within a specific range represents the second optimization constraint [16]. The acceptable voltage range is between 0.95 and 1.05 pu.

$$V_{profile} = \sum_{l}^{n} (V_i - V_{nom}) \quad (3)$$

Where;
V_i – the bus voltage i in pu
V_{nom} – the nominal voltage in pu
n – the number of buses

2.5 Metaheuristic Techniques

LSA and MLSA are the two metaheuristic approaches used in this investigation. The primary justification for employing LSA and MLSA is their superior performance in handling intricate power system study problems, as demonstrated by Syed Nasir *et al.,* [23]. Based on the enhancements made to the previous LSA, MLSA was created by Abualigah *et al.,* [24]. The key formulas utilized in LSA and

MLSA are comparable in general. To create the MLSA, four changes were made to the current LSA, as detailed by Syed Nasir *et al.,* [23]. The load flow approach used in this study is described in depth by Syed Nasir *et al.,* [23].

2.6 Research Framework

The research framework, which outlines the general methodology of this study, will be the main emphasis of this section. As seen in Figure 2, the comprehensive research framework is divided into three sections. The DNEP setup with conventional load and huge EV load penetration was the main topic of the first section. The positioning and size of DERs at the DNEP according to a five-year scenario is the second section. The final section of the article focuses on the metaheuristic LSA and MLSA methodologies for determining the ideal location and size of DERs.

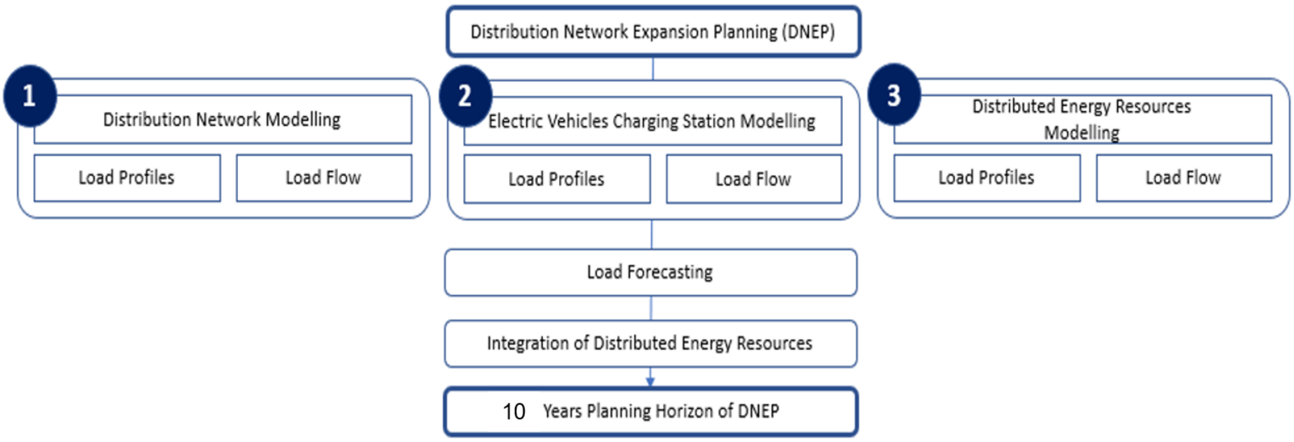

Fig. 2. Research framework

3. Results

In this research, load forecast for 10 years DNEP horizon from 2023 up to 2032 are made based on 2% annually electricity growth projection. Three scenarios have been carried out in this research. Table 2 shows the load forecast of 69-bus practical distribution network for year 2023, 2027 and 2032 together with power losses produced by the existing distribution network before penetration of any EV loads.

Table 2
Load forecast for 10 years DNEP horizon

Scenario	Real Power (MW)	Real Power Losses (MW)
Year 2023	11.125	0.1692
Year 2027	12.058	0.1990
Year 2032	13.337	0.2430

Table 3 shows the load forecast of 69-bus practical distribution network for year 2023, 2027 and 2032 together with power losses produced by the existing distribution network after massive penetration of any EV loads.

Table 3
Load forecast for 10 years DNEP horizon after massive EV loads penetration

Scenario	Real Power (MW)	Real Power Losses (MW)
Year 2023	14.345	0.2428
Year 2027	17.035	0.3775
Year 2032	21.176	0.5361

Table 4 shows the three scenarios which has been carried out in this research. From result, it shows that Year 2032 scenario gives high impact to the power loss as compared to Year 2023 scenario.

Table 4
Three scenario of EV loads in this research

Scenario	Year	No. of EV Charging Station Level 3	No. of EV Charging Station Level 2	No. of EV Charging Station Level 1	Total EV Charging Station	EVCS Load (MW)	EVCS Load (MVAr)
1	2023	20	30	80	130	3,125	1,936
2	2027	29	44	117	190	4,545	2,816
3	2032	47	71	189	307	7,352	4,556

The size of the distribution network determines how many DERs are utilized in the DNEP. Thus, the trial-and-error approach was employed in this study to determine the lowest values and the ideal range of DERs. Generally, the performance of the distribution network system as a whole may be improved by having more DERs with the ideal size. On the other hand, the goal of this research is to cover a large network with the fewest possible DERs. It will therefore be more beneficial to any utility firm. Moreover, limiting the quantity of DERs will simplify the process of figuring out where and how big to put them.

The performance of a 69-bus radial distribution system with varying numbers of installed DERs is displayed in Table 5. Table 5 is used as the basis for simulations involving varying numbers of DERs, which demonstrate that choosing five sets of DERs is necessary to meet the goal of minimizing power losses. The outcome explains why, with normal load increase and large EV load penetration, two, three and four sets of DERs are insufficient to reduce the power loss. The results showed that, in this investigation, five sets of DERs produce the greatest results. Therefore, based on the research, five sets of DERs are the minimal need for the suggested DNEP.

Table 5
Result of DERs integration

No. of DERs	2 sets		3 sets		4 sets		5 sets	
	Bus	Size (MW)	Bus	Size (MW)	Bus	Size (MW)	Bus	Size (MW)
DER 1	29	2.0000	19	1.9735	54	1.1929	55	1.2514
DER 2	19	1.9985	7	1.9988	29	1.9997	29	1.9965
DER 3	-	-	29	1.9996	7	1.9998	21	1.8793
DER 4	-	-		-	19	1.9868	12	1.9854
DER 5	-	-		-	-	-	66	1.7529
Power Loss (MW)	0.1403		0.1295		0.1029		0.0910	

Using LSA and MLSA, five DERs of different sizes and positions were randomly put for the first scenario. Thus, using appropriate settings, the LSA and MLSA optimization procedures simulated the ideal locations and sizes. For all optimization techniques, 50 populations and 50 iterations are used in this simulation. Table 6 demonstrates that DNEP documented real power losses of 0.2428 MW prior to incorporating DERs. Then, power loss may be reduced to 0.0908 MW by integrating DERs into the DNEP and optimizing using LSA and power losses can be minimized to 0.0900 MW by employing MLSA.

Table 6
Results for Scenario 1 (Year 2023)

No. of DERs	DNEP With EV loads		DNEP with EV loads with DERs (LSA)		DNEP with EV loads with DERs (MLSA)	
	Bus	Size (MW)	Bus	Size (MW)	Bus	Size (MW)
DER 1	-	-	7	1.984932	8	1.907182
DER 2	-	-	20	1.946741	52	1.524529
DER 3	-	-	55	1.219706	30	1.800618
DER 4	-	-	25	1.949643	18	1.816819
DER 5	-	-	32	1.318716	24	1.379136
Power Loss (MW)	0.3775		0.1448		0.1438	

Table 7 for Scenario 2 demonstrates that DNEP reported real power losses of 0.3775 MW prior to incorporating DERs. Then, power loss may be reduced to 0.1448 MW by integrating DERs into the DNEP and optimizing using LSA and power losses can be minimized to 0.1438 MW by employing MLSA.

Table 7
Results for Scenario 2 (Year 2027)

No. of DERs	DNEP With EV loads		DNEP with EV loads with DERs (LSA)		DNEP with EV loads with DERs (MLSA)	
	Bus	Size (MW)	Bus	Size (MW)	Bus	Size (MW)
DER 1	-	-	57	1.132409	54	1.36587
DER 2	-	-	9	1.750718	30	1.989247
DER 3	-	-	29	1.977306	65	1.893856
DER 4	-	-	19	1.904963	8	1.898926
DER 5	-	-	67	1.625194	20	1.929184
Power Loss (MW)	0.2428		0.0908		0.0900	

Table 8 for Scenario 3 demonstrates that DNEP reported real power losses of 0.3775 MW prior to incorporating DERs. Then, power loss may be reduced to 0.1448 MW by integrating DERs into the DNEP and optimizing using LSA and power losses can be minimized to 0.1438 MW by employing MLSA. The findings demonstrate that include five sets of DERs in the DNEP has a significant impact, particularly when it comes to reducing power loss. In addition, when compared to the LSA approach, the MLSA technique found a better way to reduce the power losses.

Table 8
Results for Scenario 3 (Year 2032)

No. of DERs	DNEP With EV loads		DNEP with EV loads with DERs (LSA)		DNEP with EV loads with DERs (MLSA)	
	Bus	Size (MW)	Bus	Size (MW)	Bus	Size (MW)
DER 1	-	-	55	1.762753	32	1.81751
DER 2	-	-	9	1.973743	21	1.992453
DER 3	-	-	26	1.946042	55	1.708559
DER 4	-	-	32	1.260114	12	1.973482
DER 5	-	-	21	1.987579	25	1.849026
Power Loss (MW)	0.5361		0.2221		0.2206	

4. Conclusions

This research paper exhibits successful development of a method to minimize power losses in the distribution network system for realistic 11kV 69-bus radial distribution network due to the massive penetration of EV Charging Station along the 10 years of DNEP horizon. Integration of DERs with correct sizing and placement have been adopted in this research to minimize the power losses in the distribution network system during the DNEP process. The design of DERs is based on needs of the specified distribution network system. The findings demonstrate that integration of five sets of DERs in the DNEP process has a significant impact, particularly when it comes to reducing power loss. LSA and MLSA are the two metaheuristic approaches used in this research to optimize the sizing and placement of DERs for the integration with the distribution network system during the DNEP process. In addition, when compared to the LSA approach, the MLSA technique found a better way to reduce the power losses.

For the future works, the combination of integration of Capacitor Banks and DERs into DNEP process considering massive penetration of EVCS will be carried out to further improve the performance of existing distribution network system [25,26]. Furthermore, meta-heuristic improved or hybrid meta technique will be adopted based on its ability to optimize the multi-objective in this research.

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