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Optimal Distribution Network Reconfiguration *via* the Integration of Distributed Generation Penetration using Meta-Heuristic Technique

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ABSTRACT

Ensuring the reliability of power distribution to customers is a challenge for the Distribution Network. It faces various issues such as the need for stable and resilient supply, increasing power costs, support for demand growth, environmental sustainability and the advancement of distributed generating technologies. Additionally, the implementation of the Incentive Based Regulation (IBR) and the reform of the energy market require greater efficiency and innovative products and services. The use of smart and digital technology allows utilities to involve users more actively, but it also demands new network design requirements [1]. Distribution networks used to distribute power from the transmission network to energy customers [2]. Distribution network planning (DNP) methodologies have mostly focused on finding the appropriate locations and sizes for system parts including substations, feeders, transformers, circuit breakers and capacitors to meet the expanding load and ensure power supply reliability. DNP often reduces investment, operating and power losses. The planning horizon predicts load demand for the classic DNP situation, where DG units are negative loads [3]. This study introduces meta-heuristic techniques to optimize the reconfiguration of the distribution system and the installation of DG units for reducing power losses and enhancing voltage profiles. The techniques are based on Modified Lightning Search Algorithm (MLSA) and tested on a 145-bus distribution system model with solar DGs and load profile.

1. Introduction

As the electric power system undergoes rapid transformation, it is imperative to acknowledge that traditional models, which heavily rely on fossil-fuelled power generation, may no longer effectively cater to the increasing demand for sustainable development. This is particularly evident in regions with limited access to fossil energy resources, underscoring the urgent need to transition towards renewable energy sources [4-6]. The incorporation of distributed generation (DG) units in

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electrical systems has demonstrated their flexibility and ability to directly inject power into the DN. These renewable DG units harness inexhaustible green power extracted from nearby energy sources such as solar cells (PV) or concentrators, as well as wind turbines (WT) [7,8].

The methods proposed in [9-11] aim to identify the most appropriate allocation of DGs and ensure optimal reconfiguration for the distribution system. These approaches primarily focus on determining the suitable capacities of solar DGs and analysing their coordinated operation within a DN. To optimize DG capacities, the method takes into consideration the timing of maximum power generation for solar and wind DGs. However, uncertainties in power generation may result in the actual capacities of DGs exceeding the optimized capacities. The main objective of this research is to minimize active power loss and voltage deviation in the DN. Network reconfiguration is another technique employed to achieve this objective. By reconfiguring the DN, the voltage profile at bus nodes is improved, network reliability is enhanced and the burden on heavily loaded lines as well as power losses are reduced [12,13].

Network reconfiguration is becoming increasingly important to improve the security and cost-effectiveness of distribution systems. This involves changing the structure of the electrical grid to optimize its performance. By modifying the grid, network reconfiguration can solve issues like voltage and current overloads, making the power system more reliable. It can also improve the distribution of current and voltage, reducing network losses and enhancing economic performance in grid operations. The most suitable option for a cost-effective approach is the reconfiguration of the DN, which involves identifying a new network topology by manipulating switches while maintaining the radial structure of the DN. The optimal reconfiguration of the radial distribution network (ODNR) aims to find the most efficient DN topology using optimization techniques from existing literature. The main objectives are to minimize losses, ensure compliance with voltage and current limits, connect all loads and preserve the radial structure. By integrating optimization techniques, the ODNR problem can be solved more efficiently, leading to faster convergence towards an optimal solution [14-17].

1.1 Review of Related Work

1.1.1 Distributed generation (DGs)

Local generation of renewable energies can be facilitated through the implementation of various systems, devices and locations, including panels, government buildings, geothermal heat pumps, biomass and combined heat and power. The use of solar and wind power for electricity generation offers a sustainable solution that minimizes carbon dioxide emissions. The development of cost-effective technologies is crucial for enhancing efficiency and decreasing the cost of electricity production per kilowatt-hour.

Renewable energy sources (RES) play a significant role in the smart power grid due to their low maintenance requirements, long lifespan and environmentally friendly characteristics. Technologies such as wind and photovoltaic (PV) are examples of renewable energy sources that are non-exhaustive and non-polluting [18]. However, solar, hydro, wind and geothermal energy sources are inherently unpredictable, leading to technical challenges like system instability, reduced reliability and inefficiency. Therefore, the provision of reserve energy is essential to maintain the system's stability and reliability [18,19].

DERs have become more prevalent in electric distribution networks in the last two decades due to affordable technology, increased customer demand for reliable electricity and the liberalization of the electricity market [20]. However, the integration of DERs into the distribution system can pose challenges such as voltage rise and bidirectional power flow [21]. To tackle these challenges, there is a need to improve the management approach of the distribution system [22]. Traditionally, distribution systems were designed for one-way power transmission from substations to customers. However, the high penetration of DERs has led to reverse power flows, which can create reliability challenges that distribution system operators (DSOs) must address [23].

1.1.2 Distribution network reconfiguration (DNR) in system planning

Distribution networks are essential for energy delivery, yet they encounter obstacles like power loss and voltage instability. Various strategies, such as compensating reactive power, increasing operating voltage, balancing loads and expanding wire sections, can be utilized to tackle these challenges. However, the implementation of these solutions may come at a high cost. An alternative method is network reconfiguration, which involves adjusting the network structure through the manipulation of switches to minimize power loss while still meeting operational demands. This cost-effective approach has the potential to greatly enhance power systems [24].

This is achieved by changing the state of sectionalizing and tie-switches [25]. Enhancing the performance of radial distribution networks through reconfiguration is becoming more and more feasible. Both manual and automatic switching techniques can effectively manage all loads, minimize power loss, improve system security and enhance power quality. By reconfiguring the network, the burden on network components can be reduced. This process involves opening and closing sectionalizing and tie switches, which changes the network's configuration. These switches ensure that the network remains radial and powers all loads. Researchers have explored various approaches to address the issue of power distribution network reconfiguration [26]. DNR is one of the best ways to improve power quality indices and distribution network performance by relocating tie-lines to ensure radial design. Tie-lines, generally open points can be repositioned as mentioned by Mishra *et al.,* [27]. Repositioning tie-lines using mathematical, heuristic and metaheuristic optimization methods from wide literature. These publications dispute the best distribution network configurations.

To recapitulate the study proposed to address the research gap mentioned earlier, the significance of this research can be summarized as follows:

i. To optimize DNR using Lightning Search Algorism (LSA) and Modified Lightning Algorism (MLSA) integrated with DGs to determine the most suitable locations for DGs.
ii. The network reconfiguration method is implemented with the objective of enhancing the voltage profile and minimizing power losses in the DN.

2. Methodology

The present study aims to validate the reconfiguration method and its outcomes by employing the widely recognized IEEE 145 bus system, as depicted in Figure 3. Distribution networks are conventionally designed as interconnected networks; however, during operation, they undergo reorganization into a radial tree-like structure. Consequently, distribution systems are partitioned into subsystems of radial feeders, comprising a sequence of both normally closed switches and normally open switches. Hybrid algorithms were utilized during the system reconfiguration process to determine the optimal switching sequence and size of DG units within the network. The most suitable locations for DG units were identified using sensitivity factor and index method [28]. It was assumed that the DG units integrated into the radial system would operate at unity power factor, with voltage constraints kept within ±5% of the nominal value. To prevent reverse power flow in the network, the capacities of DG units were constrained within a range of 20% to 85% of the total power load demands of the radial distribution networks [29].

The main objective of this section is to present the research framework that outlines the overall procedure of the study. To conduct the simulation, two metaheuristic approaches, namely LSA and MLSA, are employed in this investigation [30]. The comprehensive research framework is divided into three sections, as illustrated in flowchart Figure 1. The initial phase of the process involves developing a model for the practical 145-bus radial distribution system, incorporating the standard load. Subsequently, a backward-forward load flow analysis is used to determine the voltage and current levels at all buses and lines. Moving forward, the subsequent section focuses on the placement and sizing of DG that will have an impact on the load side of the distribution system [30]. Finally, the third section focuses on reconfiguring the distribution network to identify the optimal placement of switches, considering the projected load growth for the next five years. The aim of this reconfiguration is to enhance the voltage profile and reduce active power losses within the distribution system [31].

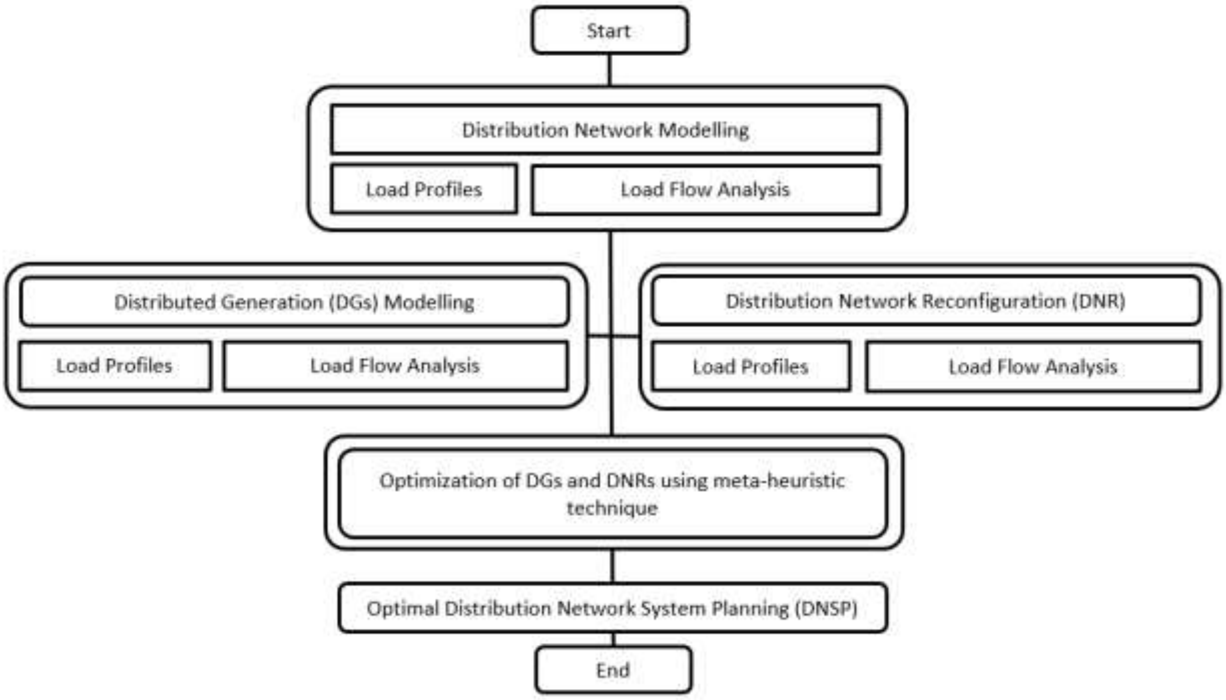

Fig. 1. Research flowchart

Before implementing the proposed methodology, it is of utmost importance to ascertain the appropriate number of DGs to maximize the benefits of the system. To determine the suitable DG number, it will be based on the typical range of solar installations in Malaysia. The study encompasses a total of six variables, which include three options for placement and three different sizes of DGs. Each of these parameters will have specific constraints that need to be satisfied. The placement of DGs will be determined by minimizing power loss and improving the voltage profile at various bus locations. Since this involves two objective functions, a multi-objective approach will be adopted using weight summation. The essential formulas for the multi-objective analysis can be seen in Eqs. (1) and (2) below:

$$OBJ = \omega_1 Losses_{rel} + \omega_2 V_{profile} \quad (1)$$

$$\omega_1 = \omega_2 = 0.5 \quad (2)$$

Where;

OBJ is refered to multi − objective function
ω_1 and ω_2 are weighted coefficient
$Losses_{real}$ is active power losses of distribution network
$V_{profile}$ is voltage at all busses

3. System Modelling

The subsequent sections will focus on the modelling of the distribution system, incorporating DG and the prediction of load growth. Following that, the emphasis will transition to determining the appropriate formula for calculating power loss, voltage profile and load growth. Ultimately, the attention will be directed towards the technical analysis conducted using the PSS ADEPT software in this research.

3.1 Distribution System Modelling

Considering the standard load and operation of DGs, the distribution system has been developed. It is specifically designed to replicate the actual distribution system utilized by the utility company in Malaysia, which caters to a diverse range of areas including residential, commercial and industrial zones. To evaluate the integration of solar DGs into the distribution system, the 11kV 145-bus radial distribution system was selected for analysis and simulation, as outlined in Figure 2.

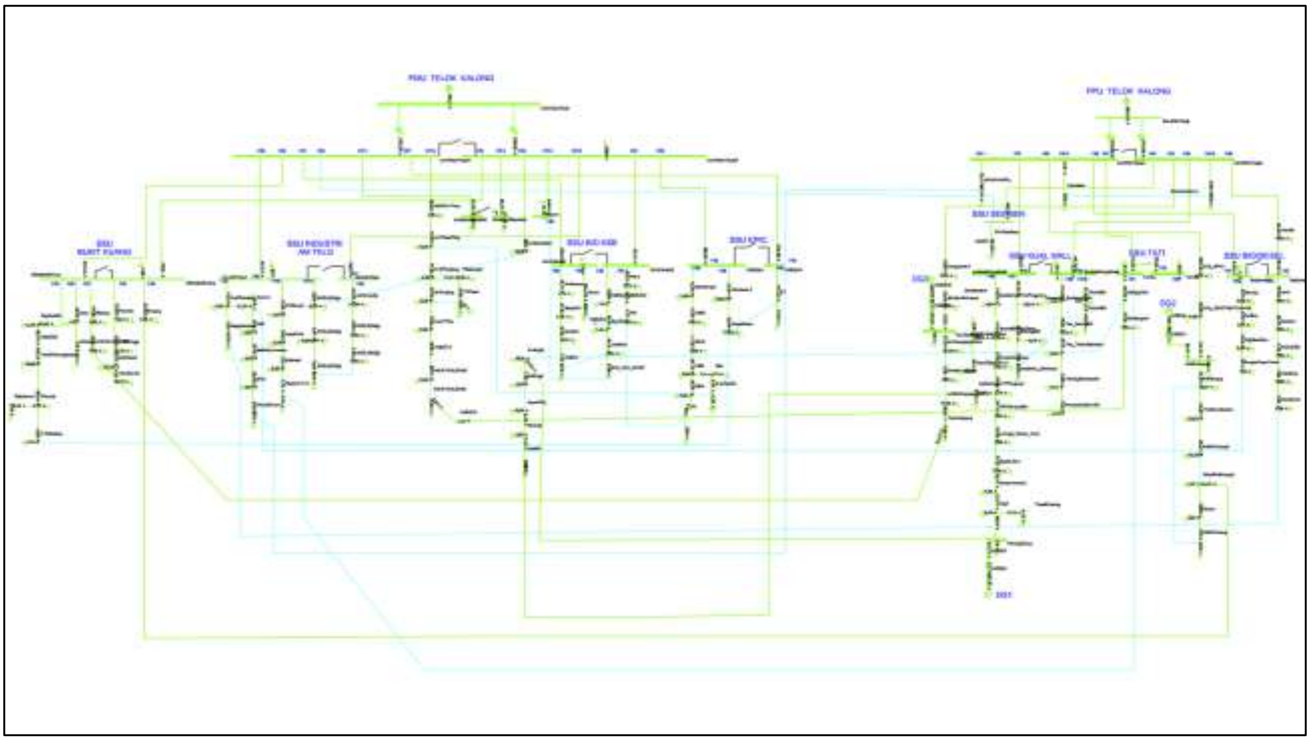

Fig. 2. 11 kV practical 145-bus radial distribution system

The practical distribution system generally consists of a higher number of branches due to customer demand and the distance from the nearest bus. Load data is established on the peak load observed during the afternoon, as highlighted in Figure 3.

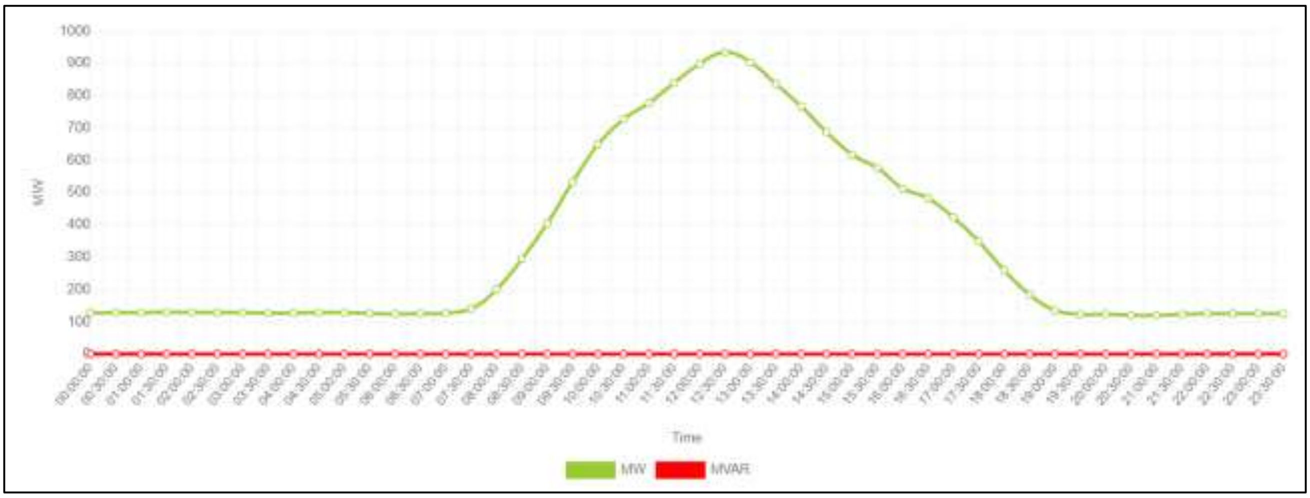

Fig. 3. Peak hour of DGs penetration (highest at 12:30 at noon)

More comprehensive information on load and line data are in Tables 1 and 2. The existing load of the distribution network is recorded as 28.292 MW and 14.570 MVAr.

Table 1
Load data for 145-bus radial distribution system

Bus No.	Load (MW)	Load Mvar	Bus No.	Load (MW)	Load Mvar	Bus No.	Load (MW)	Load Mvar
1	0.540	0.270	26	0.016	0.008	51	0.023	0.012
2	0.075	0.038	27	0.004	0.002	52	0.011	0.005
3	0.039	0.020	28	0.005	0.003	53	0.039	0.019
4	0.032	0.016	29	0.018	0.009	54	0.039	0.019
5	0.025	0.013	30	0.010	0.005	55	0.017	0.009
6	0.018	0.009	31	0.018	0.009	56	0.009	0.004
7	0.007	0.004	32	0.006	0.003	57	0.106	0.053
8	0.098	0.049	33	0.051	0.025	58	0.035	0.017
9	0.062	0.031	34	0.204	0.102	59	0.024	0.012
10	0.034	0.017	35	0.205	0.103	60	0.021	0.011
11	0.032	0.016	36	0.046	0.023	61	0.012	0.006
12	0.030	0.015	37	0.043	0.022	62	0.063	0.032
13	0.016	0.008	38	0.044	0.022	63	0.052	0.026
14	0.002	0.001	39	0.017	0.009	64	0.045	0.023
15	0.014	0.007	40	0.017	0.009	65	0.007	0.004
16	0.016	0.008	41	0.024	0.012	66	0.238	0.119
17	0.013	0.007	42	0.025	0.012	67	0.171	0.085
18	0.008	0.004	43	0.025	0.012	68	0.069	0.035
19	0.020	0.010	44	0.007	0.004	69	0.062	0.031
20	0.015	0.007	45	0.763	0.382	70	0.050	0.025
21	0.006	0.003	46	0.053	0.026	71	0.043	0.022
22	0.004	0.002	47	0.030	0.015	72	0.022	0.011
23	0.080	0.040	48	0.027	0.013	73	0.007	0.004
24	0.047	0.024	49	0.024	0.012	74	0.012	0.006
25	0.031	0.016	50	0.001	0.000	75	0.007	0.004

Bus No.	Load (MW)	Load Mvar	Bus No.	Load (MW)	Load Mvar	Bus No.	Load (MW)	Load Mvar
76	0.103	0.051	101	0.108	0.054	126	0.077	0.038
77	0.031	0.015	102	0.095	0.047	127	0.074	0.037
78	0.146	0.073	103	0.091	0.045	128	0.073	0.036
79	0.000	0.000	104	0.080	0.040	129	0.073	0.037
80	0.028	0.014	105	0.061	0.031	130	0.066	0.033
81	0.107	0.053	106	0.054	0.027	131	0.053	0.027
82	0.581	0.291	107	0.023	0.012	132	0.047	0.023
83	0.464	0.232	108	0.010	0.005	133	0.001	0.001
84	0.036	0.018	109	0.003	0.001	134	0.046	0.023
85	0.023	0.011	110	0.001	0.001	135	0.038	0.019
86	0.023	0.011	111	0.001	0.000	136	0.022	0.011
87	0.018	0.009	112	0.000	0.000	137	0.020	0.010
88	0.012	0.006	113	0.157	0.079	138	0.018	0.009
89	0.006	0.003	114	0.143	0.072	139	0.014	0.007
90	0.004	0.002	115	0.137	0.068	140	0.001	0.001
91	0.092	0.046	116	0.101	0.050	141	0.021	0.010
92	0.039	0.019	117	0.088	0.044	142	0.007	0.004
93	0.030	0.015	118	0.067	0.033	143	0.171	0.086
94	0.023	0.012	119	0.000	0.000	144	0.018	0.009
95	0.013	0.007	120	0.154	0.077	145	0.019	0.009
96	0.003	0.002	121	0.04	0.0.22			
97	0.027	0.013	122	0.028	0.014			
98	0.013	0.007	123	0.014	0.007			
99	0.241	0.121	124	0.112	0.056			
100	0.000	0.000	125	0.097	0.049			

Table 2
Line data for 145-bus radial distribution system

From Bus	To Bus	R (ohms)	X (ohms)	From Bus	To Bus	R (ohms)	X (ohms)	From Bus	To Bus	R (ohms)	X (ohms)
132kVBusTKLG	11kVPMUTKLGA	0.000	0.000	11kVFSKSB2	Petra	0.161	0.152	StnMykPetronas	TMNTlkKalong	0.265	0.160
11kVFSKSB1	11kVPMUTKLGA	0.161	0.152	Petra	KPK	0.265	0.160	TMNTlkKalong	bktkuangsejahtera	0.265	0.160
11kVFSKSB1	Haven	0.195	0.083	11kVPMUTKLGB	11kVFSTKlg1	0.161	0.152	DesaDarulIman	Bktkuangsejahtera	0.265	0.160
11kVFSKSB1	WHSamudera	0.161	0.152	centurypulp	11kVFSTKlg1	0.161	0.152	DesaDarulIman	c/sBktKUangsejahtera	0.265	0.160
Slumb29	WHSamudera	0.161	0.152	centurypulp	MIEL5 (tklg)	0.161	0.152	c/sBktKUangsejahtera	TmnKetapang	0.265	0.160
Slumb29	SSKB2	0.161	0.152	MIEL5 (tklg)	MIEL4 (tklg)	0.161	0.152	11kVPPUTKLGA	BioDiesel1	0.161	0.152
SSKSB2	TUBEX	0.161	0.152	BB2SSUBktKua	BKuang	0.195	0.083	HHA	BioDiesel2	0.161	0.152
11kVPMUTKLGA	11kVFSTKlg2	0.161	0.152	BB2SSUBktKua	BKuang	0.195	0.083	Dayang	Drillex	0.161	0.152
11kVFSTKlg2	IndTlkKalung	0.161	0.152	BKuang	PatodPinKuang2	0.568	0.117	PejElwishEnv	Drillex	0.161	0.152
IndTlkKalung	Mustari	0.161	0.152	PCicar	PatodPinKuang2	0.195	0.083	BengkelTepatTeknik	PejElwishEnv	0.161	0.152
Mustari	UBF	0.161	0.152	BB2SSUBktKua	TmnKmn	0.161	0.152	11kVPPUTKLGA	C/S_SPAN	0.161	0.152
UBF	SalutaryAvenue	0.161	0.152	SMBktKuang	PCicar	0.265	0.160	C/S_SPAN	C/S_JMBTNBKTKUANG	0.161	0.152
SalutaryAvenue	pfce	0.161	0.152	4-PBTinggi	TmnKmn	0.161	0.152	C/S_JMBTNBKTKUANG	SKBktKuang	0.161	0.152
pfce	AlvichEnviro	0.161	0.152	4-PBTinggi	EastCoast	0.161	0.152	SKBktKuang	RMBKuang	0.265	0.160
IndTlkKalung	SmpgPanchor	0.265	0.160	EastCoast	TmnMeriah	0.161	0.152	RMBKuang	TmnRkytBestari	0.159	0.105
MIEL1 (tklg)	11kVFSTKlg2	0.161	0.152	11kVPMUTKLGB	Bitumen	0.161	0.152	TmnRkytBestari	RMBktKuang2	0.265	0.160
MIEL1 (tklg)	MIEL2 (tklg)	0.161	0.152	11kVPMUTKLGB	NODE63	0.195	0.083	CsuValser	11kVPPUTKLGA	0.161	0.152
MIEL3 (tklg)	MIEL2 (tklg)	0.161	0.152	NODE63	Slumberger	0.161	0.152	11kVPPUTKLGA	LHSSSUKijalMall	0.080	0.095
MIELno.6	11kVFSTKlg2	0.161	0.152	Slumberger	KSB5	0.161	0.152	S-STPuchong	PSemangat	0.524	0.094
MIELno.6	HotelTati	0.161	0.152	KSB5	OMS	0.161	0.152	TmnPinggiran	LHSSSUKijalMall	0.161	0.152
HotelTati	SSchool	0.161	0.152	OMS	KSB1	0.195	0.083	TmnPinggiran	BdrKijal01	0.161	0.152
SSchool	PlastikTATI	0.265	0.160	KSB1	OBM	0.265	0.160	Kompleks_Usahawan	BdrKijal01	0.161	0.152
BB1SSUBktKua	11kVPMUTKLGA	0.161	0.152	OBM	LPK	0.265	0.160	RMKijal	S-SKijal	0.265	0.160
BB1SSUBktKua	Ing.PamStn	0.195	0.083	Silo	KSB1	0.195	0.083	LHSSSUKijalMall	bombaKijal	0.161	0.152
TmnBktkuangDamai	Ing.PamStn	0.195	0.083	IronPasific	Silo	0.195	0.083	bombaKijal	SawmillPantaiTimur	0.161	0.152

TmnBktkuangDamai	TPermai	0.265	0.160	NODE63	Westwsarf	0.161	0.152	SawmillPantaiTimur	PrumhnMentauh	0.195	0.083
4-PSDelima	TPermai	0.195	0.083	Westwsarf	KimiaCecair	0.161	0.152	H-PTBygLuar	PrumhnMentauh	0.195	0.083
PolisMerin	TPermai	0.195	0.083	11kVPMUTKLGB	RHSLionPlateMill	0.161	0.152	H-PTBygLuar	HPTBerayoDlm	0.265	0.160
BB1SSUBktKua	SMSis	0.265	0.160	c/sEpicSolar	11kVPMUTKLGB	0.161	0.152	c/sKjal_Water_Tank	HPTBerayoDlm	0.265	0.160
SKCukai	SMSis	0.195	0.083	PlastikTATI	TATIa	0.265	0.160	c/sKjal_Water_Tank	GiatMARA	0.265	0.160
BB1SSUBktKua	Slipway	0.265	0.160	11kVPPUTKLGA	TATIa	0.080	0.095	tmnberisnenas	GiatMARA	0.265	0.160
Slipway	C/STMNKTPNG2	0.265	0.160	11kVPPUTKLGB	Handal	0.161	0.152	Kijal	Tmnberisnenas	0.265	0.160
11kVPMUTKLGA	LHSLionPlateMill	0.161	0.152	Handal	BioDiesel2	0.161	0.152	TkomBKmning	Kijal	0.524	0.094
11kVPMUTKLGA	NODE64	0.161	0.152	BioDiesel1	Dayang	0.161	0.152	S-SKijal	TmnKijalJaya	0.265	0.160
ET	NODE64	0.265	0.160	HHA	Baseera	0.161	0.152	S-SKijal	SSSpgTati	0.195	0.083
11kVPMUTKLGA	SS132kvTiox.	0.161	0.152	Baseera	PIONEER	0.161	0.152	RMKijal	LayoutKij	0.265	0.160
H-PTkomTKlg	SS132kvTiox.	0.161	0.152	PIONEER	HapSeng	0.161	0.152	LayoutKij	SKKijal	0.265	0.160
H-PTkomTKlg	S-STPuchong	0.195	0.083	SecaDyme	HapSeng	0.161	0.152	SKKijal	Satelit	0.265	0.160
KimiaCecair	4-PSDelima	0.265	0.160	11kVPPUTKLGB	RHSSUKijalMall	0.080	0.095	H-PTBygLuar	KgMentauh	0.195	0.083
PSemangat	ITCPupuk	0.265	0.160	Perumahan_Eastern Steel	RHSSUKijalMall	0.161	0.152	SKBERISMERAGA	SawmillPantaiTimur	0.265	0.160
S-STPuchong	SKTkalong	0.195	0.083	Perumahan_Eastern Steel	Tmn_Serindit2	0.161	0.152	TMNPERMATA1	SKBERISMERAGA	0.265	0.160
SKTkalong	ITCPupuk	0.265	0.160	Tmn_Serindit2	Tmn_TitianSelumbar	0.161	0.152	11kVPPUTKLGA	UNICHAMPb,	0.161	0.152
KuariTKlg	RMMTKALONG2	0.265	0.160	TmnKijalMentauh2	Tmn_TitianSelumbar	0.161	0.152	SSSpgTati	TATIa	0.265	0.160
RMMTKALONG1	RMMTKALONG2	0.265	0.160	TmnKijalMentauh2	PerumahanSerindit	0.161	0.152	SKalongan2	SSSpgTati	0.195	0.083
11kVPMUTKLGA	SSUSeeSen	0.080	0.095	Tekstil01	RHSSUKijalMall	0.161	0.152				
11kVPMUTKLGB	11kVFSKSB2	0.161	0.152	Tekstil02	Tekstil01	0.161	0.152				
SKTkalong	KuariTKlg	0.195	0.083	SSUSeeSen	11kVPPUTKLGB	0.080	0.097				
Halliburton	BayuPurn	0.265	0.160	11kVPPUTKLGB	SunwayQuarry	0.161	0.152				
Vastalux	BayuPurn	0.265	0.160	kuangcentre	11kVPPUTKLGB	0.161	0.152				
S/S_WH_34&35	Vastalux	0.161	0.152	StnMykPetronas	kuangcentre	0.161	0.152				

3.2 DGs Modelling

The effects of solar DGs on power losses and voltage profile are dependent on the quantity of DGs and their power output ratings. The specific characteristics of each solar DG system are influenced by the technology utilized in its construction, as well as the design of active and reactive power generation for the distribution network. The modelling of solar DGs involves the generation of active or reactive power, based on their technological attributes. This study primarily focuses on power loss and voltage profile; therefore, each DG will exclusively generate active power with a power factor of unity. The placement and size of the DGs will be determined through optimization results. Table 3 as display below showed the technical specification of the photovoltaic systems used as distributed generation: -

Table 3
Photovoltaics (PV) module characteristics

No.	Description	Value
1.	Maximum Power (Pmax)	340W
2.	Power Tolerance	0 to +3%
3.	Maximum Power Voltage (Vmp)	38.7V
4.	Maximum Power Current (Imp)	8.79A
5.	Open Circuit Voltage (Voc)	47.1V
6.	Open Circuit Current (Isc)	9.24A
7.	Nominal Operating Cell Temp (NOCT)	45 ± 2%
8.	Maximum System Voltage	1500VDC
9.	Maximum Series Fuse Rating	20A
10.	Operating Temperature	-40 °C to +85 °C
11.	Application Class	A
12.	Fire Class	C
13.	Weight	22.5 (kg)
14.	Dimension	1956 x 992 x 40 (mm)
15.	Standard Test Conditions (STC)	1000 W/m², AM1.5, 25°C

3.3 Power Loss and Voltage Profile

The study focuses on two primary objectives: power loss and voltage profile. In distribution systems, a cable or overhead line is commonly linked to two buses. The mathematical representation of power loss can be expressed as either Eqs. (3) or (4) [32,33].

4. Optimal Planning of Distribution Networks with Consideration DGs

To enhance the energy supply to feeder loads in distribution networks, the integration of DGs can be employed to implement efficient strategies during the network optimization procedure. The optimization of economic objectives encompasses the reduction of investment and operational expenses, mitigation of energy losses and reliability costs. Technical limitations involve equipment capacity, reliability indicators, voltage drop and the utilization of multi-objective algorithms to accommodate the radial network structure [34].

$$P_{loss} = \left(\frac{P_{ij}^2+Q_{ij}^2}{V_i}\right) R_{ij} \tag{3}$$

$$P_{loss} = \sum_{i=1}^{24} I_{rel,ij}^2 \, R_{ij} \tag{4}$$

Where;

n_n is total number of busses in the distribution network
R_{ij} are the resistance of the network
$I_{rel,ij}$ are real current of power network

The equation provided by Khasanov *et al.,* [35] offers a comprehensive explanation for determining the voltage profile at all buses. This equation is denoted as Eq. (5). Furthermore, it is crucial to enforce the constraint that all bus voltages fall within the acceptable range [36]. The acceptable voltage range spans from 0.95 pu to 1.05 pu.

$$V_{profile} = \sum_{t=1}^{24} \sum_{i=1}^{n} |V_i(t) - V_{nom}| \quad (5)$$

Where;

$V_i(t)$ is the bus voltage in $p.u.$
V_{nom} is the rated voltage in the $p.u.$
n is the number of buses

4.1 Metaheuristic Techniques

The study will concentrate on two metaheuristic approaches known as LSA and MLSA. LSA draws inspiration from lightning phenomena and is expressed in mathematical equations, while MLSA is an extension of LSA aimed at enhancing current search methods [37,38]. The selection of these techniques is grounded in their proven capabilities from previous studies. Additionally, MLSA was developed by building upon the improvements introduced to the original LSA, both of which are rooted in lightning characteristics. The specific enhancements made to the original LSA to create MLSA can be found in references [39-42].

5. Results

The main objective of the initial simulation is to identify the optimal range of solar DGs connected to the distribution system to minimize active power losses. The initial scenario involved conducting a study based on the assumption that the load in the current distribution system would remain constant. Following this, three types of DGs were utilized and randomly simulated in a practical 145-bus radial distribution system. Each selected bus will support 3 DG units. The simulation indicated a power loss of 350.97KW for a system without DGs. As a result, the initial simulation, as illustrated in Table 4, suggests that the most suitable range for solar DGs in Malaysia is between 0.5MW and 2MW. Taking into consideration the penetration level of DGs, the tested DGs consumed power ranging from 200kW to 500kW only.

Table 4
Real power losses on tested distribution network

No.	Tested on Distribution Network (DN)	Capacity of DGs (kW)			Real Power Losses	Reduction
		DG1	DG2	DG3	kW	
1.	Existing DN	0	0	0	350.97	-
2.	DN with DGs	500	200	250	344.92	1.72%
3.	DN with DGs and Reconfiguration	500	200	250	343.65	2.09%

To enhance network efficiency and voltage profile in the distribution system, network reconfiguration must be carried out by determining the optimal position of tie switches or line switches. The selection of switches for optimization is influenced by the load profile of the distribution network at each branch. Each line in the distribution network is equipped with switches for reconfiguration purposes, which can be utilized for restoring power supply during contingencies. The line with the highest network losses is identified by the switch number for further analysis and recommendation of network reconfiguration. The switch number corresponds to the tie switch, while the positions of line switches in the distribution network are outlined in Figure 4.

Power Flow Details

Name	1st Node	2nd Node	Phase	Library Ref	I(a)	I(b)	I(c)	|Vab|	|Vbc|	|Vca|	Min V	Total Branch Power		Total Losses		Total Dist	Switch
												P	Q	P	Q		
Tx1PMUTKLG	132kVBusTKLG	11kVPMUTKLGA	ABC	T132T11M30	366.84	366.84	366.84	1.02	1.02	1.02	1	6,504,478	3,142,810	18,095	171,189	0.0000	Ignore
Tx2PMUTKLG	132kVBusTKLG	11kVPMUTKLGB	ABC	T132T11M30	518.01	518.01	518.01	1.03	1.03	1.03	1	9,074,550	5,010,742	37,257	354,337	0.0000	Ignore
F#09TKLG	11kVPMUTKLGA	LHSLionPlate	Mil	A11UG240X	34.47	34.47	34.47	1.02	1.02	1.02	1	569,608	314,467	1,168	-37,820	2.1000	Ignore
F#10TKLG	11kVPMUTKLGB	RHSLionPlate	Mil	A11UG240X	99.37	99.37	99.37	1.02	1.02	1.02	1	1,656,192	990,200	9,904	-30,078	2.1000	Ignore
F#03TKLG	11kVPMUTKLGA	SS132kvTiox.	ABC	A11UG240X	30.97	30.97	30.97	1.02	1.02	1.02	1	573,299	120,292	1,568	-63,155	3.4900	1
TKLGF5	11kVPMUTKLGA	11kVFSKSB1	ABC	A11UG240X	51.23	51.23	51.23	1.02	1.02	1.02	1	-862,029	-438,629	4,057	-57,138	3.3000	2
F#08TKLG	11kVPMUTKLGB	11kVFSKSB2	ABC	A11UG240X	35.43	35.43	35.43	1.03	1.03	1.03	1	627,040	238,067	1,926	-60,382	3.3000	3
Line5~~~~~~	NODE64	ET	ABC	A11UG150X	139.29	139.29	139.29	1.00	1.00	1.00	1	-2,269,800	-1,387,564	19,939	-6,774	4.4100	4
Line42~	HPTBerayoDlm	c/sKjal_Wate	r_T	A11UG150X	29.56	29.56	29.56	1.00	1.00	1.00	1	-381,061	-397,179	1,011	-21,277	21.6200	5
F#11TKLG	11kVPMUTKLGA	BB1SSUBktKua	ABC	A11UG240X	54.17	54.17	54.17	1.02	1.02	1.02	1	-978,466	-333,292	4,320	-53,392	3.1100	6
F#02TKLG	11kVPMUTKLGB	BB2SSUBktKua	ABC	A11UG240X	71.83	71.83	71.83	1.02	1.02	1.02	1	-1,305,556	-473,509	7,629	-51,206	3.1100	7
F#04TmnKmn	BB2SSUBktKua	TmnKmn	ABC	A11UG240X	43.04	43.04	43.04	1.02	1.02	1.02	1	750,842	314,477	2,775	-56,815	6.3100	8
Line341	11kVPMUTKLGB	Bitumen	ABC	A11UG240X	161.88	161.88	161.88	1.02	1.02	1.02	1	2,696,697	1,641,771	25,393	-13,755	2.0200	9
PMUTKLG2F8	TATla	11kVPPUTKLGA	ABC	A11UG500X	72.73	72.73	72.73	1.03	1.03	1.03	1	1,220,773	602,684	6,186	-122,014	5.1000	10
Line18	11kVPPUTKLGB	RHSSSUKijalM	all	A11UG500X	62.58	62.58	62.58	1.02	1.02	1.02	1	1,094,952	323,666	7,953	-223,512	14.2600	11
Line24	11kVPPUTKLGA	LHSSSUKijalM	all	A11UG500X	82.08	82.08	82.08	1.01	1.01	1.01	1	1,403,328	550,970	13,861	-214,459	14.2600	12
Line395	C/S_JMBTNBKT	SKBktKuang	ABC	A11UG240X	93.95	93.95	93.95	1.01	1.01	1.01	1	1,365,752	1,176,671	3,812	-12,813	9.9000	13
Line437	11kVPPUTKLGA	C/S_SPAN	ABC	A11UG240X	107.59	107.59	107.59	1.02	1.02	1.02	1	1,631,275	1,275,625	16,485	-40,232	8.1000	Ignore
Line438	C/S_SPAN	C/S_JMBTNBKT	KUA	A11UG240X	98.31	98.31	98.31	1.01	1.01	1.01	1	1,451,548	1,214,689	4,175	-12,566	9.0000	14
Line236	11kVPPUTKLGB	kuangcentre	ABC	A11UG240X	72.28	72.28	72.28	1.02	1.02	1.02	1	-1,021,961	-917,930	8,548	-57,572	8.6000	15
Line469	StnMykPetron	TmnTlkKalong	ABC	A11UG150X	61.18	61.18	61.18	1.02	1.02	1.02	1	810,290	856,079	2,943	-13,232	9.9600	16
Line473	TmnTlkKalong	bktkuangseja	hte	A11UG150X	54.28	54.28	54.28	1.02	1.02	1.02	1	924,602	488,024	2,322	-13,527	10.9600	17
Tran9	33kVPPUTKLG	11kVPPUTKLGB	ABC	33T11M15	313.42	313.42	313.42	1.03	1.03	1.03	1	-5,335,997	-3,319,653	12,599	237,361	5.1000	Ignore
Tran10	11kVPPUTKLGA	33kVPPUTKLG	ABC	33T11M15	370.84	370.84	370.84	1.00	1.00	1.00	1	-6,424,492	-3,743,602	17,638	332,344	5.1000	Ignore
Line542	11kVPMUTKLGA	11kVFSTKlg2	ABC	A11UG240X	66.35	66.35	66.35	1.01	1.01	1.01	1	1,204,587	407,258	6,280	-49,450	3.0000	18
Line541	11kVPPUTKLGB	SSUSeeSen	ABC	A11UG5001C	165.99	165.99	165.99	1.03	1.03	1.03	1	-2,749,213	-1,730,436	4,708	-12,289	5.8000	19
Line413	11kVPPUTKLGA	UNICHAMPb,	ABC	A11UG240X	116.43	116.43	116.43	1.03	1.03	1.03	1	2,021,342	1,043,884	2,946	-5,682	5.5510	20
Line525	LHSSSUKijalM	bombaKijal	ABC	A11UG240X	53.67	53.67	53.67	1.01	1.01	1.01	1	883,994	508,054	2,583	-32,113	16.1500	21
Line527	bombaKijal	Saw millPanta	iTi	A11UG240X	44.00	44.00	44.00	1.01	1.01	1.01	1	696,496	447,710	1,762	-33,403	18.0800	22
Line617	11kVPMUTKLGA	NODE64	ABC	A11UG240X	138.77	138.77	138.77	1.01	1.01	1.01	1	2,298,394	1,357,684	28,594	-29,880	3.1100	Ignore
Line623	SSUSeeSen	11kVSeeSena	ABC	USER	166.02	166.02	166.02	1.02	1.02	1.02	1	2,744,505	1,742,725	12,401	49,519	6.8000	23
Line36	11kVPMUTKLGB	NODE63	ABC	A11UG185	116.07	116.07	116.07	1.02	1.02	1.02	1	2,003,515	997,169	24,077	-75,831	3.1100	24
Tran1	NODE2	NODE3	ABC	22T11M1.0	26.44	26.44	26.44	1.00	1.00	1.00	1	499,965	-62,235	2,541	20,823	25.4500	25
Tran3	NODE1	NODE6	ABC	11T0.4M1.0	18.95	18.95	18.95	1.00	1.00	1.00	1	199,987	-300,526	2,661	6,118	9.9000	26
Tran4	NODE11	NODE10	ABC	11T0.4M1.0	20.07	20.07	20.07	1.01	1.01	1.01	1	250,000	-294,000	2,987	6,870	9.9600	27

Fig. 4. The tie switch and line switches of 145-bus 11kV distribution network

For better analysis the line switches with highest losses are selected for network reconfiguration. Line switch number 10, 15 and 22 has been selected for optimum position as presented in Table 5.

Table 5
The position or location of the line switches after shift to optimum switches position

Optimization with DNR	Switch No.	Original Switch Location	Optimal Switch Location
	10	RMM Telok Kalong 1	RMM Telok Kalong 1
	15	Tmn Ketapang	Desa Darul Iman
	22	Satelite	RM Kijal

The results of the comparison between LSA and MLSA are presented in Table 6. The losses generated in the practical 145-bus radial distribution system through LSA optimization total 414.58kW, while for MLSA optimization, the losses amount to 381.98kW. These values exhibit a considerably enhanced level of stability when compared to the initial real power losses of 733.57kW subsequent to the introduction of solar DG sources.

Table 6
Simulation of optimal DGs using LSA and MLSA

Solar DGs No.	Existing distribution network	Existing distribution network integrated with Solar DGs using LSA Optimization		Existing distribution network integrated with Solar DGs using MLSA Optimization	
		Bus No.	Size (MW)	Bus No.	Size (MW)
Solar DG1	without Solar DGs	88	1.9593	122	1.6723
Solar DG2		129	1.6029	97	1.8363
Solar DG3		84	1.9264	88	1.6571
Solar DG4		31	1.2303	84	1.8675
Solar DG5		110	1.9225	110	1.9572
Real Power Losses (kW)	733.57KW	KW414.58	KW381.98		
% Losses reduction compared to existing	-	-43.484%	-47.928%		

The results of the comparison between LSA and MLSA with Distribution Network Reconfiguration (DNR) are presented in Table 7.

Table 7
Simulation of optimal DGs with DNR using LSA and MLSA

Solar DGs No.	Existing distribution network	Existing distribution network integrated with Solar DGs & DNR using LSA Optimization		Existing distribution network integrated with Solar DGs & DNR using MLSA Optimization	
		Bus No.	Size (MW)	Bus No.	Size (MW)
Solar DG1	without Solar DGs	27	1.3818	84	1.6723
Solar DG2		84	1.9912	121	1.8363
Solar DG3		91	1.8225	28	1.6571
Solar DG4		129	1.9605	87	1.8675
Solar DG5		72	1.5022	95	1.9572
Real Power Losses (kW)	733.57KW	403.76KW	KW394.95		
% Losses reduction compared to existing	-	-44.959%	-46.160%		

The practical 145-bus radial distribution system experienced losses of 403.76kW for LSA with DNR optimization and 394.95kW for MLSA with DNR optimization, indicating a more stable outcome in comparison to the initial real power losses of 733.57kW following the integration of solar DG sources. Figures 5 and 6 indicated the comparison of voltage profile between the original, LSA and MLSA optimization. Optimization using meta-heuristic technique showed some improvement and stability in voltage pattern.

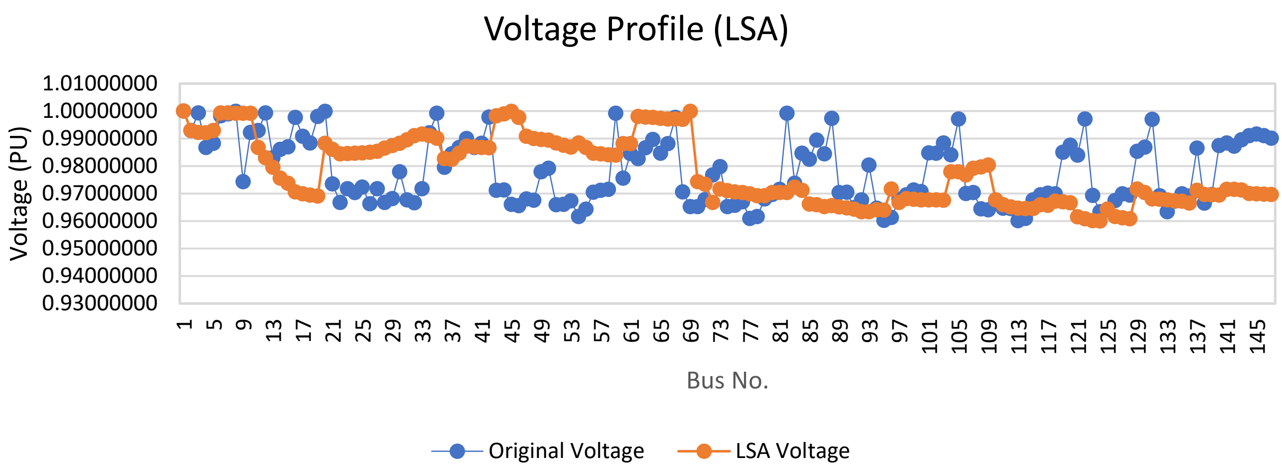

Fig. 5. Voltage profile before and after optimization of DGs using LSA

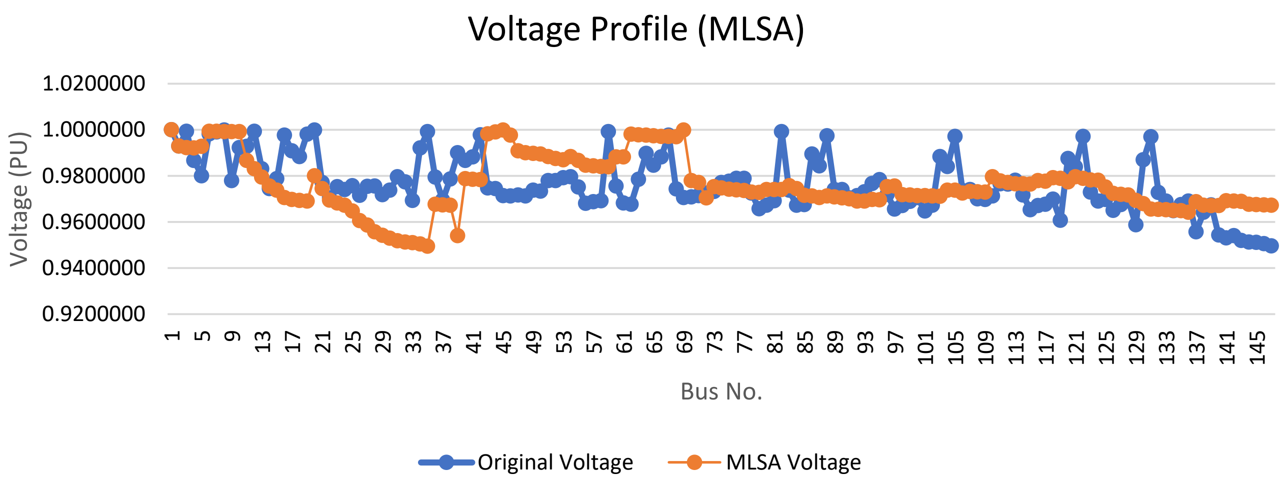

Fig. 6. Voltage profile before and after optimization of DGs using MLSA

Meanwhile Figures 7 and 8 illustrate an enhancement in the voltage profile simulation when compared to the original profile. It is essential for the voltage variance at each bus to remain within specified upper and lower limits to ensure voltage stability and power quality. The distribution system recognizes voltage limits within ±5% of the rated voltage for the load buses.

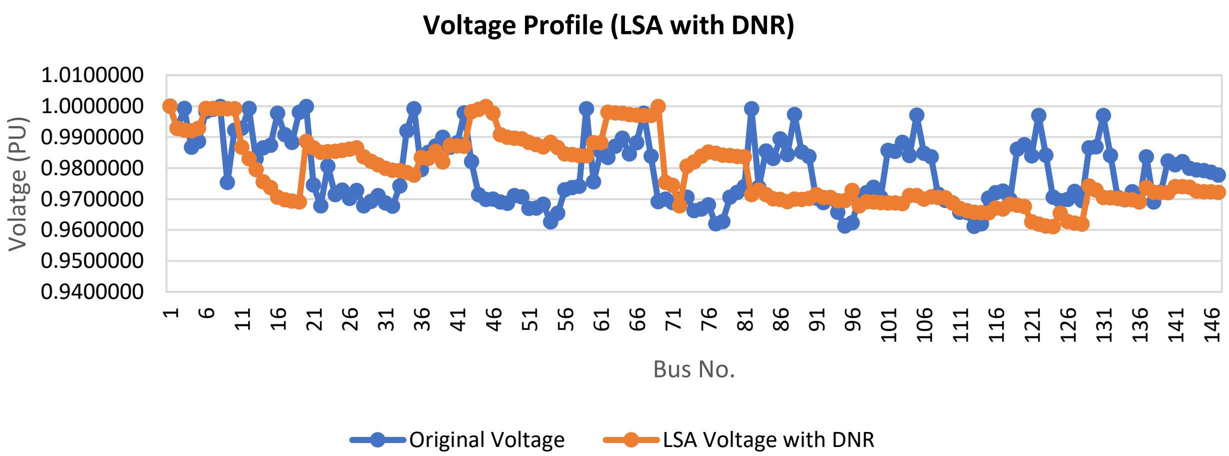

Fig. 7. Voltage profile before and after optimization of DGs with DNR using LSA

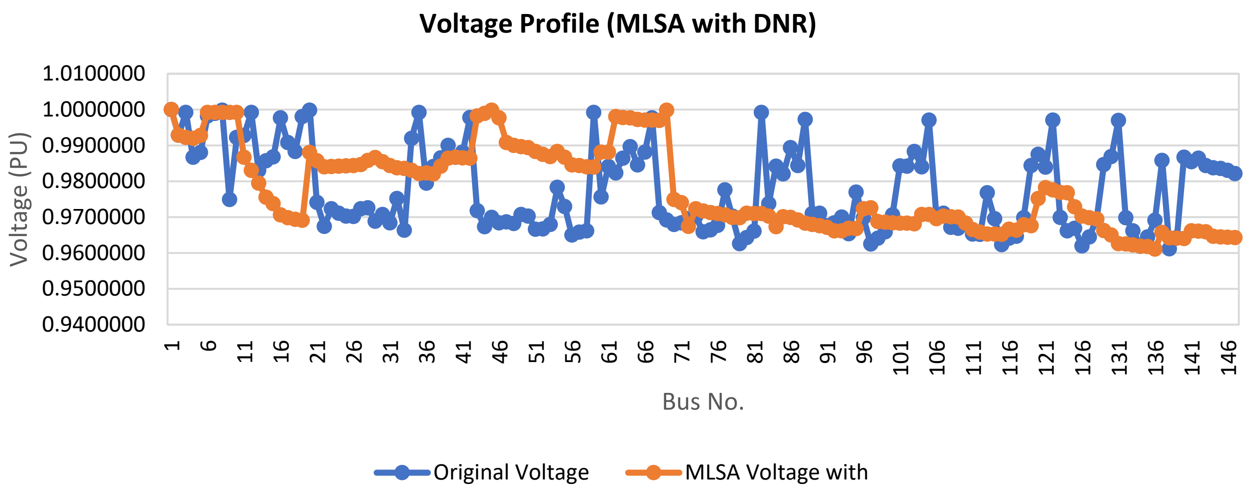

Fig. 8. Voltage profile before and after optimization of DGs with DNR using MLSA

6. Conclusions

This study demonstrates the successful application of a technique on a 145-bus network to boost the voltage profile and decrease actual network losses. Through the coordination of distributed generators (DGs), the optimal DG sizes were determined using meta-heuristic technique simulations while ensuring compliance with all constraints. Moreover, this paper also concentrates on improving the location and dimensions of solar DGs with Distributed Network Reconfiguration (DNR). The proposed technique for optimizing solar DGs with DNR is designed to reduce power loss and enhance voltage stability. The optimization issue was tackled using Local Search Algorithm (LSA) and Modified Local Search Algorithm (MLSA), with a multi-objective strategy that utilizes the weigh summation method to identify the most suitable fitness value. The detailed examination indicated that LSA performed better than MLSA, particularly in reducing power losses in the current distribution network. Although both LSA and MLSA displayed similar voltage profiles, they both exhibited significant enhancements in voltage stability compared to the existing distribution system.

In this study, the idea of evaluating the ideal placement for capacitor banks, dynamic loads, DG operation modes, the level of DG penetration and conducting an economic analysis of the system is put forward. Additionally, it is recommended to perform a reliability study on the reconfigured network and test the algorithm on an existing utility distribution network. To assess the algorithm's performance, the subsequent researcher must develop a miniature smart distribution network that replicates the contemporary utility distribution network. The proposed algorithm can be transformed into firmware and embedded into the system's controller unit. Additionally, there are various other metaheuristic algorithms that have been published, which warrant further exploration to comprehend their characteristics and evaluate the potential of combining them with other algorithms to create a more efficient and powerful algorithm.

Over the next few years, advancements in research will likely involve the integration of Battery Energy Storage Systems (BESSs) into the planning frameworks of distribution network systems (DNSP), aimed at improving the operational efficiency of the existing network, especially considering the considerable integration of DGs [43]. Furthermore, a variety of strategies, including heuristic, analytical and metaheuristic methods, are typically employed to ascertain the most effective placement and sizing of DGs and DNR [44]. The rationale for employing a metaheuristic technique in this research is its proven effectiveness in achieving optimal solutions compared to other available techniques.

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