Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 2, April 2025, pp. 861~873
ISSN: 2302-9285, DOI: 10.11591/eei.v14i2.8944

Optimization of dynamic transmission network expansion planning using binary particle swarm optimization algorithm

Faith Eseri Inyanga, Irene N. Muisyo, Keren K. Kaberere
Department of Electrical and Electronic Engineering, College of Engineering and Technology, Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya

Article Info

Article history:

Received Jun 26, 2024
Revised Oct 31, 2024
Accepted Nov 19, 2024

Keywords:

Dynamic transmission network expansion planning
Improved binary particle swarm optimization
Reactive power compensation
Transmission line loading
Voltage limits

ABSTRACT

Increasing power demand is usually met by the expansion of generation capacity. The transmission network should be expanded in tandem to ensure power is evacuated from generation points to the load centres. Inadequate power capacity causes congestion. Congestion results due to under-voltages and violation of transmission lines' loading limits. Constructing additional transmission lines is required to alleviate the congestion after measures of increasing the transmission line's transfer capability are exploited. Transmission network expansion planning (TNEP) determines the transmission lines to be added to a power system at minimal construction cost, without violating network constraints. In this research, voltage limit violations are penalized in a constrained dynamic TNEP problem for a 10-year planning horizon. The optimal location and number of new transmission lines required at minimal construction cost, and transmission losses associated with the transmission network operations are determined. Improved binary particle swarm optimization (IBPSO) algorithm is applied to optimize the dynamic transmission network expansion planning (DTNEP) results. The developed model is tested on Garver's 6-bus system using MATLAB. The construction cost for new transmission lines is minimized, and transmission losses reduced when compared to other published works without violating voltage limits (±5%) and transmission lines' thermal capacities. The transmission network system adequacy is improved.

Corresponding Author:

Faith Eseri Inyanga
Department of Electrical and Electronic Engineering, College of Engineering and Technology
Jomo Kenyatta University of Agriculture and Technology (JKUAT)
Nairobi, Kenya
Email: faithinyanga@gmail.com

1. INTRODUCTION

Over the years, increasing electricity demand has led to the addition of power generation capacity to supply the demand. With most generating plants being located far from load centres, the transmission network becomes an important infrastructure to consider in power system expansion planning. The main goal of transmission network expansion planning (TNEP) is to find optimal expansion plans [1], [2]. Much research has been published about TNEP since 1970 [3]. Some researches are related to problem solution such as differential evolution, particle swarm optimization (PSO), simulated annealing (SA) algorithm, tabu search (TS), greedy randomized adaptive search procedure (GRASP), and application of artificial intelligence tools [4]-[10], while others considered various power system parameters such as uncertainties in demand, line losses, N-1 reliability criterion, transmission line loading and system adequacy [11]-[17]. DC power flow models have also been used for TNEP problem formulations [2], [18]. However, these models do not take into account the system reactive power requirements that determine the voltage profiles, the power losses and the thermal loading of the transmission lines. Therefore, problem formulations are based on AC models to address the limitations of DC power flow models. The researchers [12], [13], problem formulation for AC power flow models active power loss without bus voltage limits. According to Inyanga *et al.* [19], the AC power flow model is applied to the static TNEP problem considering voltage limits. In 1995, Eberhart and Kennedy introduced PSO algorithm based on the simulation of the social behaviour of birds, bees or a school of fish [20]. Binary PSO (BPSO) and discrete PSO (DPSO) are two methods in the PSO technique that can be used to solve a TNEP problem [14]. BPSO however has shown better convergence results for solutions to TNEP problems [6], [11], [19], [20].

Ledezma and Alcaraz [15] proposed the use of hybridized BPSO to solve the multistage expansion problem. BPSO was applied with quadratic programming to solve the investment and operational losses cost problems respectively. The objective function was modelled with transmission losses and N-1 reliability criteria for a comprehensive approach. Line outage distribution factors were included in power flow formulation to reduce the computational effort involved with multistage TNEP. The constraints observed were power balance equality constraint, generator capacity, transmission line active power flow limit and maximum number of circuit upgrades in a transmission corridor. The authors concluded that the total cost of transmission expansion and the convergence time were considerably reduced for multi-stage TNEP. Mahdavi and Bagheri [17] studied the loading of transmission lines using BPSO while considering adequacy criterion. The authors modelled a DC power flow simulation to optimize the cost of line construction considering the maximum transmission line loading requirement in a network system while neglecting the transmission network losses. The authors concluded that adding a new transmission line while considering its thermal loading capacity produces a robust system. Research by Rocha and Saraiva [21] while considering operation and investments cost of transmission expansion modelled an optimized dynamic transmission network expansion planning (DTNEP) problem ensuring quality of supply by enforcing generator loading limits and branch flow limits in a DC-OPF model. This model was validated on Garver’s 6-bus test system and found accurate with fast convergence, despite the large computation effort. Good quality solutions were identified with fewer particles and iterations compared to continuous PSO. From the foregoing, the direct impact of enforcing voltage limits on the DTNEP objective formulation has not been demonstrated. Before the expansion, application of reactive power compensation to alleviate voltage violations and transmission lines congestion, has also not been demonstrated.

The method developed in this work, penalized voltage limits in the fitness function of the DTNEP problem and active power losses in the expansion cost formulation. Optimal selection was achieved using the improved binary particle swarm optimization (IBPSO) algorithm. IBPSO was applied to overcome the limitations of BPSO in selecting which line should be added to the power system [22]. The results evaluation revealed that IBPSO performed better than BPSO in reducing cost construction for the same number of additional lines [4], [23]. When voltage limits were considered selected additional transmission lines for expansion improved the system voltage profile and reduced the active power losses. As a result, transmission network system adequacy was increased and congestion in the network system alleviated.

The remainder of the paper is organized as follows: section 2 discusses TNEP and section 3 describes the developed solution method. Section 4 presents the study results and discussions of the same and finally. Section 5 presents the conclusion and way forward.

2. TRANSMISSION NETWORK EXPANSION PLANNING

The TNEP problem determines the number of new transmission lines, the time of addition and their location on a network system while meeting the technical, economic and environmental constraints of the system. An optimal TNEP solution provides reliable service to all customers, minimizes investment costs, reduced power losses and alleviates network congestion.

2.1. Power system congestion

TNEP arises for a power system that is unable to effectively transfer power from the point of generation to load centres. Congestion occurs when transmission networks fail to handle the desired system transactions because of violations of the system operating limits. When the thermal line and bus voltages limits are violated, and transmission line power flows exceeds the allowed reliability limits, congestion occurs [24]. System congestion creates system disturbances which cause outages in an interconnected system, and system blackouts [25]. If the system outages occur frequently, the power system components and equipment may get damaged reducing power quality. Congestion in power system needs to be corrected immediately to restore and ensure system security.

Congestion management approaches prevent thermal line and bus voltage limit violations despite demand increasing. These approaches include distributed generation, optimal power flow, load shedding, generator rescheduling, and application of flexible alternating current transformer system (FACTS) devices. The use of FACTS devices as an alternative aid in minimizing power flows in the system when the demand increases. This is achieved through improved power capability and reduced system losses. The FACTS devices are optimally located in the system at least cost, to relieve the congestion through reactive power compensation [24].

2.2. Static and dynamic transmission network expansion planning

Studies relating to TNEP are classified into static and dynamic. Static TNEP finds the optimal location and number of new lines that should be added to the transmission network in a specified planning horizon. The times when lines are constructed are not specified by the planner. The investment cost of expansion is carried out at the start of the planning horizon [26], [27]. On the other hand, dynamic TNEP is divided into multiple time intervals and the entire expansion plan is spread over the planning horizon period. Dynamic TNEP is a more realistic representation of the planning, and its implementation leads to optimal expansion results despite the complex formulations involved [28], [29].

2.3. Transmission network expansion planning optimization techniques

TNEP is an optimization problem that includes decision variables, an objective function, and constraints that can be solved using mathematical optimization, heuristic, and metaheuristic methods [18]. Mathematical optimization methods are used to solve simple and linear problems guaranteeing convergence towards best solution for a small search space area. Mathematical methods are classified using the characteristics of the programming problem they are solving. These methods have been used to solve TNEP problems and they include linear programming [4], branch and bound algorithm [30], and benders decomposition [31]. They however can be time consuming when more variables are considered [32].

Heuristic methods analyse possible options, then, based on logic, selects good quality solution using step-by-step procedures. Heuristic methods find good solutions with low computational effort, but they do not guarantee optimality or good quality of the solutions [32]. Heuristic algorithms applied to TNEP include constructive heuristic algorithm (CHAR) [27] and sensitivity analysis [33].

Metaheuristic methods apply heuristic methods iteratively to find good solutions. Although they represent a higher computational burden, they can lead to better solutions when compared to heuristic because they use smart criteria in the optimization process [32]. Metaheuristic methods applied to solve TNEP problems include genetic algorithm (GA) [5], SA [7], TS [8], GRASP [9], and PSO [20] algorithm.

3. METHOD

3.1. Case study

The developed method was tested on the widely used Garver's 6-bus system. Figure 1 represents a single-line diagram of the Garver's 6-bus system [34]. Garver's 6-bus system in Figure 1 consists of six transmission branches and five load buses with a total demand of 190 MW.

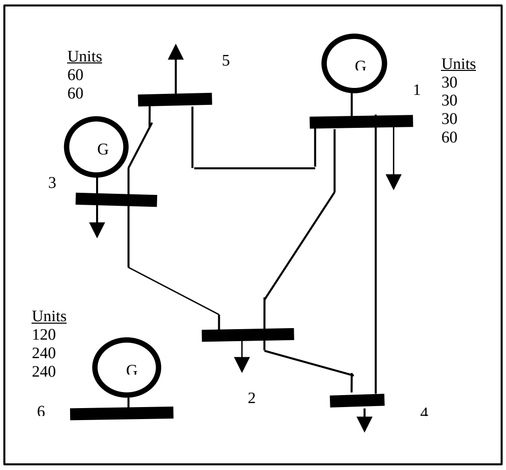


Figure 1. A single-line diagram of Garver's 6-bus system

Generation planning was assumed to have been performed and generation requirements provided for the growing load demand. Load demand was taken to increase by 10% annually at every load bus creating the need for economic and reliable TNEP to meet future load demand. Candidate transmission lines were considered on all existing and pre-planned transmission corridors. The transmission lines were assumed to be of short and medium lengths to allow the study of thermal rating of the lines and the voltage regulation effect on the transmission line's transfer capability. The bus load demand, generation capacity, length of possible transmission corridors and their construction costs were as given in [34]. The efficient operation of the transmission lines was achieved when loaded below 80% of their capacities. To connect bus 6 to the network, a new transmission line was assumed between node 6 and node 2 as the shortest candidate transmission line. A simulation was conducted to find the transmission line being overloaded and the bus voltage that violates (±5%) limits under normal operating conditions. Simulations were performed on the MATLAB R2018b platform.

3.2. Application of reactive power compensation to mitigate congestion

In this research, AC power flow was performed on Garver's 6-bus system while studying the bus voltage magnitudes and the transmission lines loading for a demand-growing system. For a given system operating condition, if the voltage at a particular bus fell below 0.95 pu, then reactive power was injected in that bus to improve the voltage. Static compensators were used to inject the reactive power in increment of 10 MVAr and the system re-evaluated for bus voltage improvement. Static compensators are cheap, with simple installation and minimal maintenance requirement. Transmission lines loading were monitored to be below their capacities. If the bus voltages were restored to within the set limits of (±5%), and transmission lines were loaded below their thermal capacities, then the system loads and generation requirements were increased. The system loads were increased by 10% on every load bus and generation units at the generating centers brought online to supply the demand. The operation was repeated until the transmission lines' loading limits were violated creating a congested system. Simulations were performed for base case, case I with reactive power resource injection, cases II and III with 10% load growth each, case VI with a further reactive power resource injection and cases V and VI with further 10% load growth each. The congested transmission network system created after reactive power compensation was taken as input to the developed methodology for DTNEP. IBPSO was applied to optimize the selected transmission lines to be added to the transmission network at a minimum cost of construction and transmission losses.

3.3. Mathematical formulation for dynamic transmission network expansion planning

The optimization in this paper was conducted by applying the IBPSO algorithm on a congested network while considering system voltage limits to obtain the optimal solution.

3.3.1. Formulation of dynamic transmission network expansion planning problem

– Objective function

The objective function of conventional TNEP is given in (1) [26]:

$$min\ C = \sum_{i=1}^{NB} \sum_{J=1}^{NB} CL_{ij} n_{ij} \tag{1}$$

where, (min C), (CL_{ij}), (n_{ij}), and (NB) represents the minimized total investment cost for transmission network expansion, the cost vector of transmission circuit added to the transmission network, the number of circuits added to the (i -j) right-of-way, and the total number of buses, respectively. The objective function formulated for this DTNEP was to get the optimal total cost of the new line construction and the cost of power losses in the network for the forecasted demand while considering voltage magnitude limits. The DTNEP objective function is given in (2):

$$minimize\ CT = \sum_{t=1}^{N} \left[(1+k)^{t-1} \sum_{i=1}^{L_c} \left(CF_{t,i} + CL_{t,i}\right)\right] \tag{2}$$

where (minimize CT), (L_c), ($CF_{t,\ i}$), (N), (k), and ($CL_{t,\ i}$) are the minimized total investment cost for the network expansion in USD, number of candidate transmission lines, cost of construction for candidate line (i) for planning year (t) in USD, total planning horizon in years, discounted inflation rate, and cost of network losses for candidate line (i) during planning year (t) respectively. Formulations for the annual cost of losses ($CL_{t,\ i}$) is given in as (3) [14]:

$$CL_{t,i} = 8760 \times C_{MWh} \times K_{loss} \times Loss \tag{3}$$

$$Loss = (LGC)^{t-1} \times P_{loss\ i} \quad (4)$$

$$P_{loss\ i} = I_i^2 \times R_i \quad (5)$$

where (C_{MWh}), (K_{loss}), and (Loss) are cost per MWh in USD, loss coefficient and total network loss at the end of a planning year, respectively. The loss coefficient simulates changes of load [13]. The total network loss at the end of a planning year is given in (4), with the load growth coefficient (LGC) to aid accurate calculation of the return on investment for cost of network loss [17]. Active power loss for added transmission line ($P_{loss\ i}$) is given in (5) where (I), (R) is the current through the transmission line (i) and the line resistance respectively. Economic and financial consideration applied to the total investment cost to cater for uncertainties associated with capital costs is given in (6) [35].

$$k = \frac{1+d}{1+r} - 1 \quad (6)$$

where (k), (d), and (r) is the inflation-adjusted discounted rate, discount rate and inflation rate. The inflation-adjusted discounted rate is carried forward to the following year through the entire planning horizon and adjusted for the difference between the nominal discount rate and the nominal inflation rate of the general price index [36], [37].

– Constraints

Several constraints are modelled in the mathematical formulation for the AC model to ensure the mathematical solutions obtained are in line with planning requirements. These constraints are as (7)-(14) [14]:

$$P(V,\theta,n) - P_G + P_D = 0 \quad (7)$$

$$Q(V,\theta,n) - Q_G + Q_D = 0 \quad (8)$$

$$P_g^{min} \leq P^g \leq P_g^{max} \quad (9)$$

$$(n_{ij} + n_{ij}^0)S^{from} \leq (n_{ij} + n_{ij}^0)S^{max} \quad (10)$$

$$(n_{ij} + n_{ij}^0)S^{to} \leq (n_{ij} + n_{ij}^0)S^{max} \quad (11)$$

$$V^{min} \leq V \leq V^{max} \quad (12)$$

$$0 \leq n_{ij} \leq +n_{ij}^{max} \quad (13)$$

$$Line_{loading} \leq LL_{max} \quad (14)$$

Variables (P_G), (Q_G), (P_D), and (Q_D) are the generator's real and reactive power vectors and the load demand real and reactive power vectors respectively. Variable (V, θ, n) gives the voltage magnitude, angle, and branch respectively. The network power balances at all the buses are given in (7) and (8). The minimum (P_g^{min}) and maximum (P_g^{max}) generator active power vector limits are given in (9). Apparent power flow through transmission lines (i-j) is given in (10) and (11). The minimum (V^{min}) and maximum (V^{max}) voltage magnitudes given in (12) are 0.95 pu and 1.05 pu, respectively, in this work. The maximum number of transmission lines that can be added along corridor (i-j) and the transmission line loading limit (LL_{max}) are given in (13) and (14) respectively.

– Fitness function

The constraints applied to the objective function find the best solution by checking for violations. The constraints are enforced by a penalty coefficient in a fitness function given in (15):

$$FF = C_T + Penalty \quad (15)$$

The penalty function combines all of the constraint violations as given in (16):

$$Penalty = \beta\left(\sum_{i=1}^{n} f(S_{Li}) + \sum_{i=1}^{NB} f(V_i)\right) \quad (16)$$

where β is the penalty coefficient taken as (10^6) applied to deviations on bus voltage magnitudes (V_i) and violations on transmission lines loading limits (S_{Li}). Constraint violations are included as penalties in the objective function of the DTNEP problem to allow for a trade-off between the constraint violations and the cost of investment. In this paper, the penalty for bus voltages and transmission loading limitations are included in the objective function formulated, forming part of the variable operation cost in the objective function to be minimized.

3.3.2. Improved binary particle swarm optimization applied to dynamic transmission network expansion planning problem

In this study, IBPSO was used to solve the DTNEP problem because it improves the performance of BPSO in selecting the additional transmission lines. Particles are presented by vectors that include problem variables. Time-varying inertia weight does not improve the convergence of the BPSO algorithm and a constant weight of 1.0 is suggested [17]. The velocity update equation is given in (17):

$$v_{id}(t+1) = v_{id}(t) + c_1 r_1 \left(p_{id} - x_{id}(t)\right) + c_2 r_2 \left(p_{gd} - x_{id}(t)\right) \tag{17}$$

where (t) is the number of algorithm iterations and the velocity ($v_{id}(t+1)$) is a real number in the range [$-V_{max}$, V_{max}]. To enable the addition of real value ($v_{id}(t+1)$) to binary value ($x_{id}(t)$) in (18), the transfer function for velocity must be defined. The transfer function limits the velocity values to between 0 and 1. IBPSO algorithm employs a probability function (18) that eliminates the drawback of big positive or negative velocity values causing a bigger probability for the particle position.

$$S'(v_{id}) = 2 \times |sigmoid(v_{id}) - 0.5| \tag{18}$$

The performance of the IBPSO algorithm is also improved by the use of previous information of position in position update [22] as given in (19) and (20):

$$If\ rand() < S'(v_{id}(t+1)),\ then$$
$$x_{id}(t+1) = exchange\ x_{id}(t) \tag{19}$$

$$,else$$
$$x_{id}(t+1) = x_{id}(t) \tag{20}$$

A constant random number, R between 0 and 1 is generated and compared to ($S(v_{id}(t+1))$) to update the position of the (i^{th}) particle. In this work, parameters used in IBPSO algorithm performed better in obtaining optimal values for the solution. The objective function parameters and IBPSO parameters [17], [35] have been initialized in Table 1.

Table 1. Objective function and IBPSO parameters

Parameter	Value	Parameter	Value	Parameter	Value
Population	20	c_2	2.3	K_{loss}	0.5
Problem dimension	15	v_{max}, v_{min}	2, -2	k	4%
Number of iterations	500	C_{MWh}	36.1	d	15%
c_1	1.7	LGC	1.1	r	10%

In Table 1, (c_1), and (c_2) are the algorithm learning factors. Parameter (v_{max}) determines the maximum change that a particle takes in a single iteration. Cost for a unit of energy is given by (C_{MWh}) and LGC. Parameters (k), (d), and (r) are the economic and financial consideration applied to the total investment cost formulation [35]. Figure 2 shows the flowchart summarizing the steps of DTNEP using IBPSO. In Figure 2, the stopping condition is attained when maximum number of iterations or minimum error requirement is attained. AC power flow is performed to evaluate the performance of each candidate transmission line as a particle in the population.

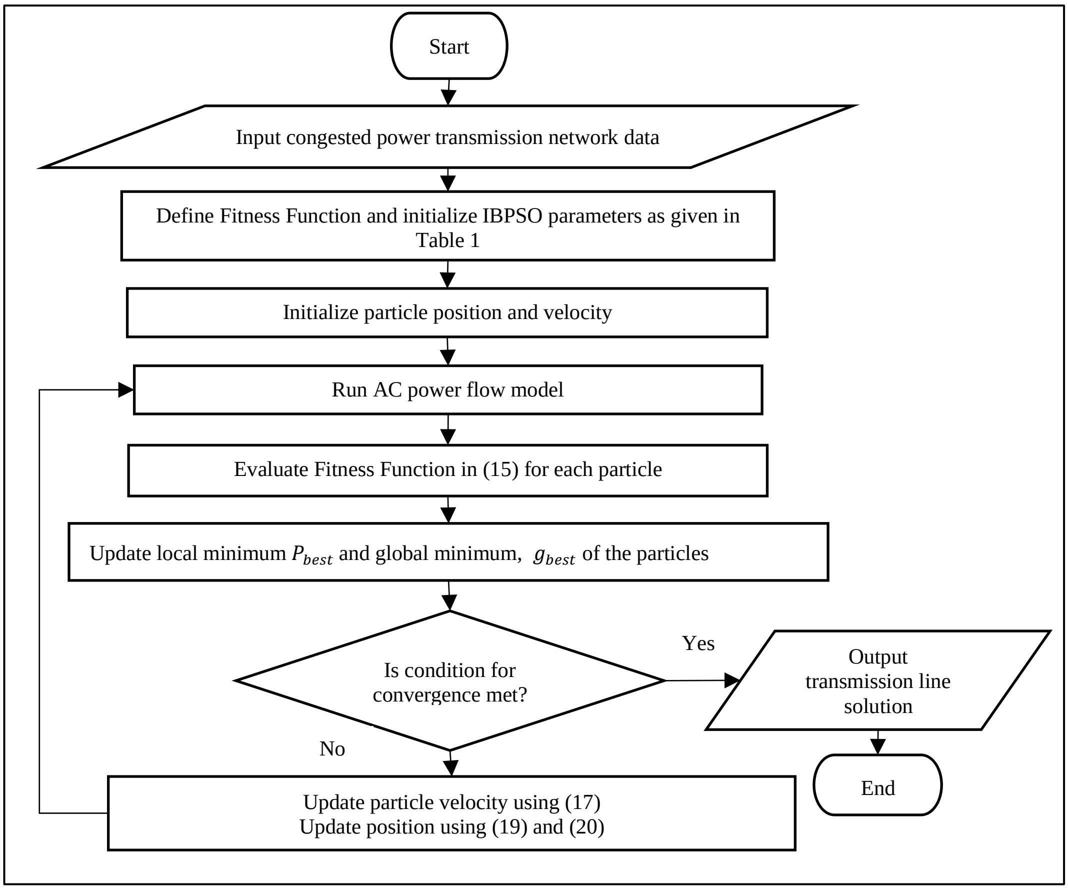


Figure 2. Flowchart of DTNEP using IBPSO

4. RESULTS AND DISCUSSION

4.1. Reactive power compensation to mitigate congestion

AC load flow simulations were carried out on Garver's 6-bus system to mitigate congestion using reactive power compensation. The system load demand was grown while monitoring transmission lines loading, bus voltage magnitude and transmission losses. Figure 3 shows the system bus voltages for the cases studied.

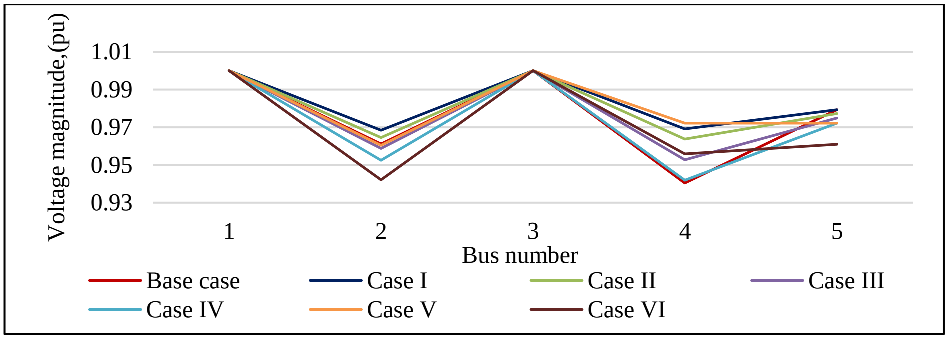


Figure 3. Garver's 6-bus system voltage magnitudes

In Figure 3, the Base case voltage magnitude at bus 4 was 0.9404, which is below 0.95 pu. Case I shows an improvement in voltage magnitude at buses 2, 4, and 5 following 10 MVAr injection at bus 4. Case II and case III voltage limits were not violated as they were within 0.95-1.05 pu range. In case IV, the voltage magnitude at bus 4 was 0.9419, below 0.95 pu. Hence additional 10 MVAr was injected at bus 4 improving the voltage profile as in case V. Case VI shows the voltage magnitude at bus 2 to be 0.9421 pu, after which the system was congested and no further reactive power compensation was performed. Voltage magnitude at buses 1 and 3 remain unchanged because they are the generator buses. Bus voltage magnitudes drop to below-defined limits because of the resistance increase from increasing current flow. The addition of loads increases the active and reactive power demand, causing the current to increase; hence, resistance increases, affecting the system voltage regulation. Consumer loads operate at specific voltages by design. Some devices however are unable to meet their rated limits and as a result, consume an amount of current which could lead to voltage differences in the network. Transmission line loading was also monitored, and the results are presented in Figure 4.

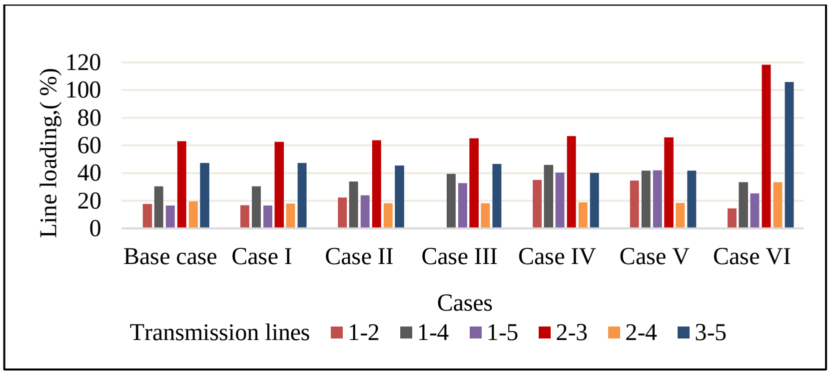


Figure 4. Garver’s 6-bus system transmission lines’ loading

In Figure 4, all the transmission lines loading for base case, case I, case II, case III, case IV, and case V are below the thermal loading capacity limit of 80%. Case VI, however, shows violations in transmission lines (2-3) and (3-5) which exceeded their thermal loading limit at 118.45% and 105.91% loading respectively. Voltage magnitude and thermal loading limits being violated are characteristics of a congested power system that justifies transmission network expansion. Figure 5 gives the system's active power losses for the studied cases.

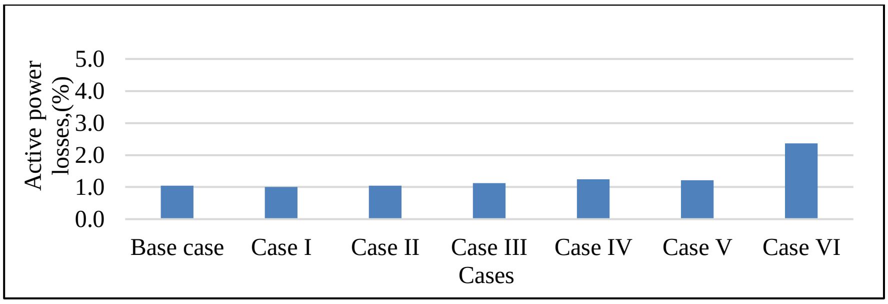


Figure 5. Garver’s 6-bus system active power losses

In Figure 5, as load demand increased, the transmission line losses also increased. There was a drop in the active power losses in case I, from 1.048% for the base case to 1.005% and also in case V, from 1.248% for case IV to 1.212% after injection of reactive power. Consequently, transmission network system adequacy and transmitted active power were also improved. Active losses for case VI increased to 2.3612% up on further load increase.

4.2. Application of improved binary particle swarm optimization to dynamic transmission network expansion planning

DTNEP was carried out to alleviate the system congestion created by the growing system. IBPSO algorithm was applied to optimize the DTNEP results. Figure 6 shows the convergence curve for IBPSO in comparison to BPSO. In Figure 6, BPSO converges faster than IBPSO. However, IBPSO explores the search space more, by jumping particles out of local optima achieved by equations given in (18)-(20). IBPSO has increased precision in selecting optimal solutions. The output was an optimal set of transmission lines whose addition to the transmission network reduced the transmission lines' construction cost and lowered the transmission losses.

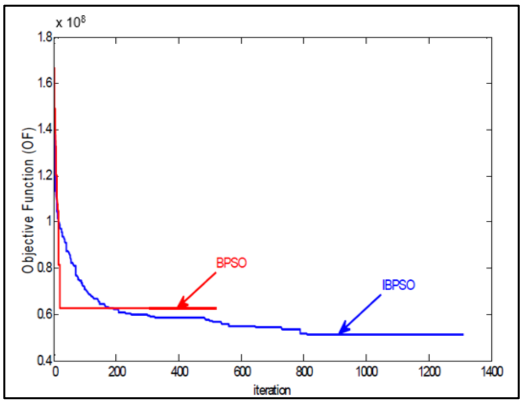


Figure 6. Convergence curves for BPSO and IBPSO algorithms

4.3. Dynamic transmission network expansion planning results

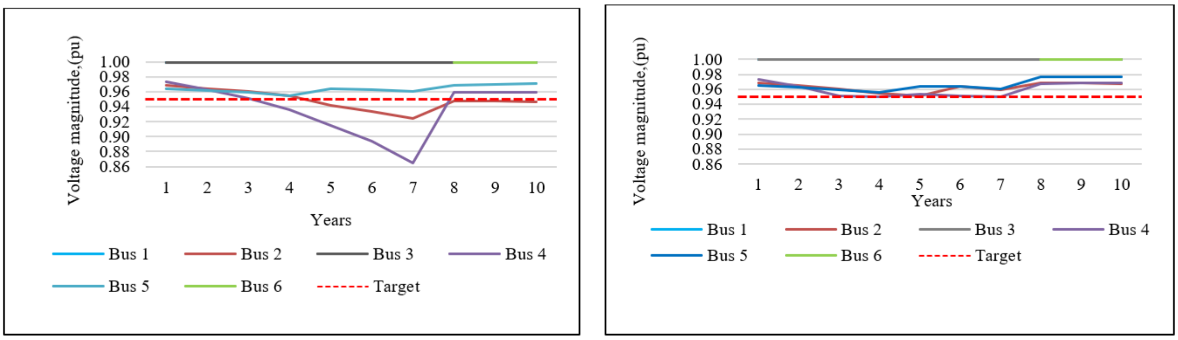
Simulation of the DTNEP resulted in the selection of an optimal set of transmission lines to be added to the transmission network system. The additional transmission lines are presented in Table 2. In Table 2, the best topology found using BPSO is one transmission line in corridor n_{3-5}, four in corridor n_{2-6}, and two in corridor n_{4-6}, with an actual value of investment obtained by formulation (2) projected to 200 million US dollars. Topology result is validated using linear programming [3] and linear population size reduction-success history based differential evolution with semi adaptation hybrid- covariance matrix adaptation (LSHADE-SPACMA) algorithm [23]. The best topology found using IBPSO was one transmission line each in corridors n_{2-3}, n_{3-5}, and n_{1-5}, and two each in corridors n_{2-6} and n_{4-6}. The total value of the investment using formulation (2) was projected to be 190 million USD. The cost of investment using the IBPSO algorithm is lower than the BPSO algorithm by 5%. IBPSO algorithm therefore produced better results with minimal expansion cost compared to BPSO. It is worth noting that the additional number of transmission lines obtained with both BPSO and IBPSO were seven.

Table 2. Additional transmission lines

	LP [3] LSHADE-SPACMA [23]	BPSO	IBPSO
Additional lines	3-5, 2-6*4, 4-6*2	3-5, 2-6*4, 4-6*2.	2-3, 3-5, 1-5, 2-6*2, 4-6*2
Construction cost (in million USD)	200	200	190

IBPSO was applied to DTNEP to select the optimal transmission lines added to the network while growing the load demand annually. The developed methodology was carried out for two scenarios in this work; ignoring bus voltage magnitude limits and considering voltage limits. Considering voltage magnitude limits, 6 additional lines, two in corridor n_{2-3} and one each in corridors n_{1-4}, n_{1-5}, n_{3-5}, and n_{3-6} were required increasing the construction cost to 286 million USD, excluding a penalty of 100,000 USD for voltage violations at bus 4. From year 8, the pre-planned bus 6 is connected to the network by additional lines n_{2-6}, n_{3-6}, and n_{4-6}. The system voltage profile, transmission lines loading and active power losses were studied under the two scenarios while increasing load demand annually and the results are presented in Figures 7-9. Figure 7 shows the bus voltage magnitudes over the 10-year planning horizon.

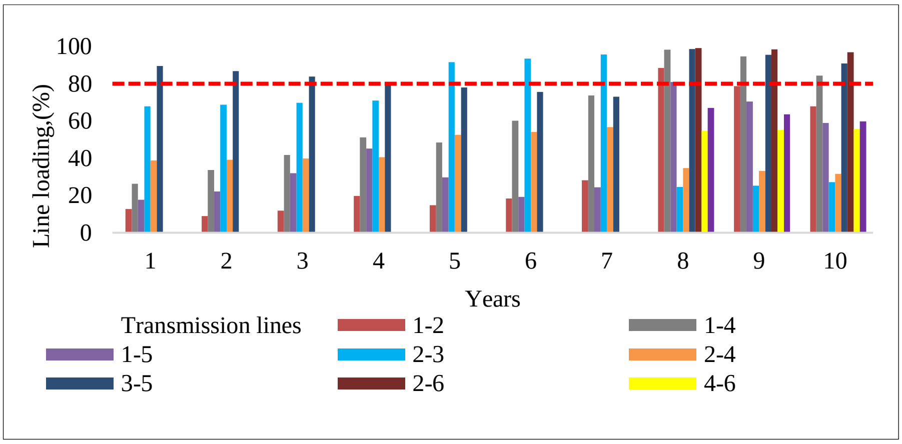
In Figure 7(a), through the expansion period, voltage magnitudes at buses 2 and 4 fell below the target of 0.95 pu. In year 7, bus 4 recorded the lowest voltage magnitude of 0.8649 pu. After considering voltage magnitude limits as in Figure 7(b), all the bus voltage magnitudes were above the target. Voltage magnitudes at bus 4 in year 7 were penalized 100,000 USD for limit violation as in the equation given in (16). Figure 8 shows the transmission lines loading over the 10-year planning horizon.



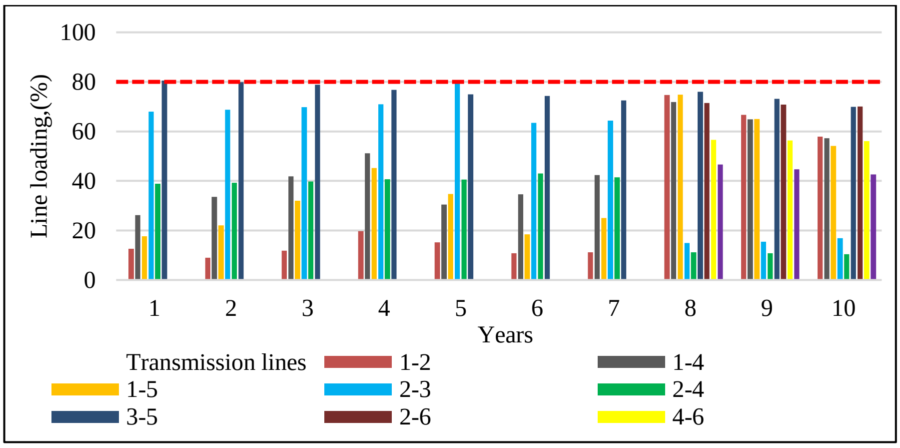
(a) (b)

Figure 7. Year-on-year bus voltage magnitudes variation: (a) without and (b) considering voltage limits

In Figure 8(a), all transmission lines' loading fell below 100% thus power system was considered operational. However, the results show that lines 3-5 in years 1 through 3, and 8 through 9, 2-3 in years 5 through 8, 1-4 and 2-6 each in the years 8 through 10 were above the target of 80% line loading. Lines 2-3 and 3-5 were each loaded up to 99% of their capacities in year 8. When voltage limits were considered in Figure 8(b), the transmission line loading for the lines were reduced to below the target. When the system voltage profile improved, transmission lines' reactive power requirement reduced, increasing transmission system adequacy for power transfer. System active power losses are represented in Figure 8 for the two scenarios; without and with voltage magnitude limit consideration over the 10-year planning horizon.



(a)



(b)

Figure 8. Year-on-year transmission lines loading: (a) without and (b) considering voltage limits

In Figure 9, the active power losses not considering voltage limits are higher in comparison to when voltage magnitude limits are considered. Active power losses record the highest of 6.05% when neglecting voltage magnitude limits in expansion year 8. Considering the voltage limit reduces loss from 6.05% to 4.72% in year 8, and from 2.12% to 1.93% in year 5, with the reduction effect evident through to final expansion in year 10. Power loss is inversely proportional to the square of the voltage. When the system voltage profile is improved, the transmission line loading is also reduced, causing active power loss to lower. The active power losses are a cost of operating the system, and efforts to economically lower the losses results to savings in the investment cost.

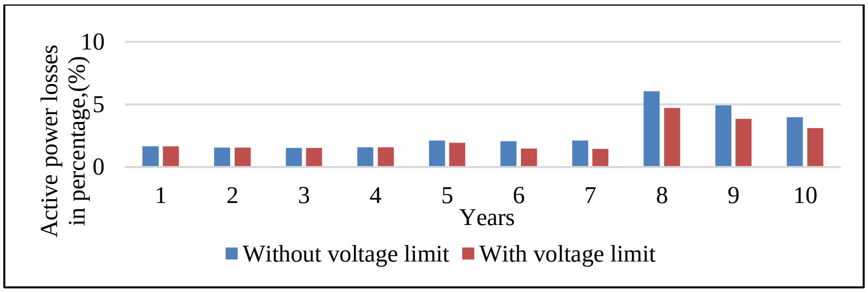


Figure 9. Garver's 6-bus active power losses

5. CONCLUSION

A DTNEP using AC model is proposed in this paper and the IBPSO algorithm applied for optimization. The developed methodology took into account the creation of congestion through load growth and an increase in generation capacity to meet the demand. Reactive power was applied to eradicate the congestion for the demand growing system until the system could no longer operate adequately, thus justifying transmission network expansion. Construction cost for additional transmission lines and the cost of active power losses were included in the cost calculation. Bus voltage magnitude limits and transmission lines loading constraints were also modelled to prevent excursions beyond defined limits. The developed methodology models voltage limit constraint in two scenarios, neglecting and considering voltage limits to show the role of voltage limits on the transmission line transfer capability and power system overall efficiency. Transmission losses increased exponentially as transmission lines became heavily loaded. Eliminating the system congestion showed a voltage-stable and uncongested network system. Although additional lines were needed to cater to the voltage requirement in the system, the transmission lines' adequacy was improved due to reduced reactive power resources and the eradication of congestion in the transmission system. The transmission lines loading was loaded below 80% of their capacities. The operation cost resulting from transmission losses was lowered by 23.19%. The expansion costs were higher for voltage consideration because extra transmission lines were needed to accommodate system overloads for voltage stability. The DTNEP studies show that voltage limit consideration improves system adequacy and eliminates system congestion. The studies on Garver's 6-bus system show that the developed method can be implemented on large power systems such as IEEE 30 and IEEE 118 bus systems. Hybridization of IBPSO algorithm can be applied to solve the DTNEP problem to improve speed of convergence for IBPSO.

ACKNOWLEDGEMENTS

The authors would like to thank the Jomo Kenyatta University of Agriculture and Technology postgraduate researchers for their helpful discussions and suggestions towards the research work.

REFERENCES

[1] H. Zhang, V. Vittal, G. T. Heydt, and J. Quintero, "A mixed-integer linear programming approach for multi-stage security-constrained transmission expansion planning," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 1125–1133, May 2012, doi: 10.1109/TPWRS.2011.2178000.

[2] H. Jiang, E. Du, M. Miao, and N. Zhang, "Stochastic Transmission Expansion Planning Considering the Transmission Overload Risk," in *IEEE Power and Energy Society General Meeting*, IEEE, Aug. 2019, pp. 1–5, doi: 10.1109/PESGM40551.2019.8973678.

[3] L. L. Garver, "Transmission Network Estimation Using Linear Programming," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 7, pp. 1688–1697, Sep. 1970, doi: 10.1109/TPAS.1970.292825.

[4] T. Sum-Im, G. A. Taylor, M. R. Irving, and Y. H. Song, "Differential evolution algorithm for static and multistage transmission

expansion planning," *IET Generation, Transmission and Distribution*, vol. 3, no. 4, pp. 365–384, Apr. 2009, doi: 10.1049/iet-gtd.2008.0446.

[5] A. R. Abdelaziz, "Genetic algorithm-based power transmission expansion planning," in *Proceedings of the IEEE International Conference on Electronics, Circuits, and Systems*, IEEE, 2000, pp. 642–645, doi: 10.1109/ICECS.2000.912959.

[6] J. Kennedy and R. C. Eberhart, "Discrete binary version of the particle swarm algorithm," in *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, IEEE, 1997, pp. 4104–4108, doi: 10.1109/icsmc.1997.637339.

[7] R. Romero, R. A. Gallego, and A. Monticelli, "Transmission system expansion planning by simulated annealing," in *IEEE Power Industry Computer Applications Conference*, IEEE, 1995, pp. 278–283, doi: 10.1109/pica.1995.515195.

[8] E. L. Da Silva, J. M. A. Ortiz, G. C. De Oliveira, and S. Binato, "Transmission network expansion planning under a Tabu Search approach," *IEEE Transactions on Power Systems*, vol. 16, no. 1, pp. 62–68, 2001, doi: 10.1109/59.910782.

[9] S. Binato, G. C. De Oliveira, and J. L. De Araújo, "A Greedy Randomized Adaptive Search Procedure for transmission expansion planning," *IEEE Transactions on Power Systems*, vol. 16, no. 2, pp. 247–253, May 2001, doi: 10.1109/59.918294.

[10] T. Al-Saba and I. El-Amin, "The application of artificial intelligent tools to the transmission expansion problem," *Electric Power Systems Research*, vol. 62, no. 2, pp. 117–126, Jun. 2002, doi: 10.1016/S0378-7796(02)00037-8.

[11] I. D. J. Silva, M. J. Rider, R. Romero, and C. A. Murari, "Transmission network expansion planning considering uncertainness in demand," in *2005 IEEE Power Engineering Society General Meeting*, IEEE, 2005, pp. 1424–1429, doi: 10.1109/pes.2005.1489297.

[12] F. Zhang, Z. Hu, and Y. Song, "Mixed-integer linear model for transmission expansion planning with line losses and energy storage systems," *IET Generation, Transmission and Distribution*, vol. 7, no. 8, pp. 919–928, Aug. 2013, doi: 10.1049/iet-gtd.2012.0666.

[13] H. Shayeghi, M. Mahdavi, A. Kazemi, and H. A. Shayanfar, "Studying effect of bundle lines on TNEP considering network losses using decimal codification genetic algorithm," *Energy Conversion and Management*, vol. 51, no. 12, pp. 2685–2691, 2010, doi: 10.1016/j.enconman.2010.06.003.

[14] Astuty and T. Haryono, "Novel binary PSO algorithm based optimization of transmission expansion planning considering power losses," in *IOP Conference Series: Materials Science and Engineering*, Apr. 2016, pp. 1–9, doi: 10.1088/1757-899X/128/1/012023.

[15] L. F. F. Ledezma and G. G. Alcaraz, "Hybrid Binary PSO for Transmission Expansion Planning Considering N-1 Security Criterion," *IEEE Latin America Transactions*, vol. 18, no. 3, pp. 545–553, Mar. 2020, doi: 10.1109/TLA.2020.9082726.

[16] M. Mahdavi, H. Monsef and R. Romero, "Reliability effects of Maintennace on TNEP considering Prevetive and Correlative repairs," in *IEEE Transactions on Power SystemsI*, vol,32, no.5, pp. 3768-3781, Sept 2017, doi: 10.1109/TPWRS.2016.2640178

[17] M. Mahdavi and A. Bagheri, "BPSO applied to TNEP considering adequacy criterion," *American Journal of Neural Networks and Applications*, vol. 4, no. 1, pp. 1–7, 2018, doi: 10.11648/j,ajnna.20180401.11.

[18] R. Hemmati, R. A. Hooshmand, and A. Khodabakhshian, "Comprehensive review of generation and transmission expansion planning," *IET Generation, Transmission and Distribution*, vol. 7, no. 9, pp. 955–964, Sep. 2013, doi: 10.1049/iet-gtd.2013.0031.

[19] F. E. Inyanga, I. N. Muisyo, and K. K. Kaberere, "Static Transmission Network Expansion Planning Considering Voltage Limits," in *IEEE AFRICON Conference*, IEEE, Sep. 2023, pp. 1–6, doi: 10.1109/AFRICON55910.2023.10293350.

[20] A. Slowik, "Particle Swarm Optimization," in *The Industrial Electronics Handbook - Five Volume Set*, IEEE, 2011, pp. 1942–1948, doi: 10.1007/978-3-319-46173-1_2.

[21] M. C. Da Rocha and J. T. Saraiva, "A multiyear dynamic transmission expansion planning model using a discrete based EPSO approach," *Electric Power Systems Research*, vol. 93, pp. 83–92, 2012, doi: 10.1016/j.epsr.2012.07.012.

[22] H. Nezamabadi-Pour, M. Rostami-Shahrbabaki, and M. M. Farsangi, "Binary Particle Swarm Optimization: challenges and New Solutions," *The Journal of Computer Society of Iran (CSI) On Computer Science and Engineering (JCSE)*, vol. 6, pp. 21–32, 2008.

[23] M. M. Refaat, S. H. E. A. Aleem, Y. Atia, Z. M. Ali, and M. M. Sayed, "Multi-stage dynamic transmission network expansion planning using lshade-spacma," *Applied Sciences (Switzerland)*, vol. 11, no. 5, pp. 1–22, Feb. 2021, doi: 10.3390/app11052155.

[24] S. Riyaz, R. Upputuri, and N. Kumar, "Congestion Management in Power System—A Review," *Lecture Notes in Electrical Engineering*, vol. 699, pp. 425–433, 2021, doi: 10.1007/978-981-15-7994-3_39.

[25] A. Narain, S. K. Srivastava, and S. N. Singh, "Congestion management approaches in restructured power system: Key issues and challenges," *Electricity Journal*, vol. 33, no. 3, pp. 1–8, Apr. 2020, doi: 10.1016/j.tej.2020.106715.

[26] H. Seifi and M. S. Sepasian, "Power System Planning, Basic Principles," in *Power Systems*, vol. 49, 2011, pp. 1–14, doi: 10.1007/978-3-642-17989-1_1.

[27] R. Romero, C. Rocha, M. Mantovani, and J. R. S. Mantovani, "Analysis of heuristic algorithms for the transportation model in static and multistage planning in network expansion systems," *IEE Proceedings: Generation, Transmission and Distribution*, vol. 150, no. 5, pp. 521–526, 2003, doi: 10.1049/ip-gtd:20030725.

[28] R. García-Bertrand and R. Mínguez, "Dynamic Robust Transmission Expansion Planning," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 2618–2628, Jul. 2017, doi: 10.1109/TPWRS.2016.2629266.

[29] M. D. Khardenvis and V. N. Pande, "Optimal static and dynamic transmission network expansion planning," *Evolving Systems*, vol. 11, no. 1, pp. 1–14, Mar. 2020, doi: 10.1007/s12530-019-09314-4.

[30] S. T. Y. Lee, K. L. Hicks, and E. Hnyilicza, "Transmission expansion by branch-and-bound integer programming with optimal cost — capacity curves," *IEEE Transactions on Power Apparatus and Systems*, vol. 93, no. 5, pp. 1390–1400, Sep. 1974, doi: 10.1109/TPAS.1974.293869.

[31] S. Granville *et al.*, "Mathematical decomposition techniques for power system expansion planning: analysis of the linearized power flow model using the Benders decomposition technique," in *Electric Power and Research Institute*, USA, Technical Report, EPRI-EL-5299, 1988.

[32] M. Mahdavi, C. S. Antunez, M. Ajalli, and R. Romero, "Transmission Expansion Planning: Literature Review and Classification," *IEEE Systems Journal*, vol. 13, no. 3, pp. 3129–3140, 2019, doi: 10.1109/JSYST.2018.2871793.

[33] M. V. F. Pereira and L. M. V. G. Pinto, "Application of sensitivity analysis of load supplying capability to interactive transmission expansion planning," *IEEE Transactions on Power Apparatus and Systems*, vol. 104, no. 2, pp. 381–389, Feb. 1985, doi: 10.1109/TPAS.1985.319053.

[34] R. Romero, A. Monticelli, A. Garcia, and S. Haffner, "Test systems and mathematical models for transmission network expansion planning," *IEE Proceedings: Generation, Transmission and Distribution*, vol. 149, no. 1, pp. 27–36, 2002, doi: 10.1049/ip-gtd:20020026.

[35] N. H. Sohtaoglu, "The effects of economic parameters on power transmission planning," in *MELECON '98. 9th Mediterranean Electrotechnical Conference. Proceedings (Cat. No.98CH36056)*, IEEE, 2002, pp. 941–945, doi: 10.1109/melcon.1998.699366.

[36] J. K. Delson, “Engineering economics literature on inflation,” *IEEE Transactions on Power Systems*, vol. 7, no. 1, pp. 73–80, 1992, doi: 10.1109/59.141689.
[37] F. Cassidy and G. W. Schirra, “Treatment of inflation in engineering economic analysis,” *IEEE Transactions on Power Apparatus and Systems*, vol. 96, no. 3, pp. 1027–1035, May 1977, doi: 10.1109/T-PAS.1977.32418.

BIOGRAPHIES OF AUTHORS

Faith Eseri Inyanga is a graduate student at Jomo Kenyatta University of Science and Technology (JKUAT) pursuing a master’s degree in Electrical and Electronics Engineering (Power systems). She received her B.Sc. degree in Electrical and Electronic Engineering (2016) from Moi University (Kenya). Her research interests include power systems and transmission network expansion planning. She can be contacted at email: faithinyanga@gmail.com.

Irene N. Muisyo is a Lecturer in the Department of Electrical and Electronic Engineering, JKUAT Kenya, where she has served since 2011. She earned her B.Sc. degree in Electronic and Computer Engineering (2010) and M.Sc. in Electrical Engineering (2018) from JKUAT, and her Ph.D. in Electrical Engineering (2022) from Pan African University Institute for Basic Sciences Technology and Innovation (PAUSTI). Her research interests include renewable energy technologies, power electronics, electric mobility, climate change and sustainability, and machine learning applications in power systems. She can be contacted at email: muisyoirene@jkuat.ac.ke.

Keren K. Kaberere is a Senior Lecturer in the Department of Electrical and Electronic Engineering, JKUAT Kenya where she has served since 1993. She received her B.Sc. degree in Electrical Engineering (1993) and M.Sc. in Electrical and Electronic Engineering (1999) from the University of Nairobi (Kenya), and her Ph.D. in Electrical Engineering (2006) from the University of Cape Town (South Africa). She is also an energy consultant. Her research interests include power system stability, energy management, power economics, and energy policy formulation. She can be contacted at email: kkanuthu@eng.jkuat.ac.ke.