

Transmission Network Expansion Planning Using Nose Curve Index

by

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Abstract

Power systems are becoming more sensitive and complex due to the rapid increase in power demand. As a result, power systems experience voltage instability, line overloading and power system blackouts. In response, utility companies are forced to plan for short-term and long-term grid expansion to meet the system requirements. The optimal transmission expansion plan must be determined prior to implementation. However, it has always been difficult to find the optimal solution to the problem in an actual power system due to its large scale, complexity, and various uncertainties. Several techniques are used to solve the constrained transmission expansion planning problem. This paper focuses on the conventional approach and proposes a modified approach which considers the nose curve index as a constraint. The main objective of planning is to minimize investment costs needed for new network elements while meeting necessary operation constraints. A system power flow analysis is performed using the analytical software PSS®E, and the resulting nose curves are plotted using Microsoft Excel. The grid network of Tanzania is chosen as the reference power system.

Keywords: Transmission expansion, Voltage instability, Dynamic programming, Voltage profile, Nose curve index

1. Introduction

The voltage instability is one of the main causes of power system blackout. Most of the previous power system blackouts that happened worldwide were caused by voltage instability¹⁾. Voltage instability can be defined as the failure of an electrical power system to sustain the voltage magnitudes at all buses remain the same after the electrical power system is being exposed to a disturbance²⁻⁶⁾. The grid networks are subjected to transmission expansion planning to meet the future power demand while satisfying the system reliability conditions at the least cost investment. The main purpose of transmission network expansion planning is to determine appropriate time, location, and capacity of transmission lines to be added to the power system⁷⁾. The transmission network expansion planning can be considered as static which focuses on planning for a single year or dynamic which focuses on several years⁸⁾. In practical, power system problems are often formulated with some constraints imposed on their variables⁹⁾. Each planning

constraints are to be satisfied to reach the optimal solution. The voltage profile is a critical constraint considered for short-term and long-term transmission expansion planning problem decision making.

In finding the optimal solution of the problem in a practical power system has always been a challenging issue due to its large dimension, complexity, and various uncertainties. There are several techniques used to solve the constrained transmission expansion planning problem. Dynamic Programming is one of the techniques used for multistage decision problems and originally was developed in 1950s by Bellman⁷⁾. It is a widely used technique in power system expansion planning studies. It is a multistage decision problem which can be decomposed into a sequence of single stage problems, the stages can be different times, different spaces, or different levels and solved successively⁷⁾.

In this study the conventional transmission expansion planning approach is considered. The paper also proposes a new modified transmission expansion planning which considers the nose curve index (voltage sensitivity factor) as a key constraint to system expansion⁶⁾. The base case, conventional approach and proposed approach results will be compared. In testing the effectiveness of the proposed

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approach, the Tanzania grid network is used to plot the nose curves.

The nose curves are obtained by performing system power flow simulation. For every series of power flow, the load of the electrical power system is increased until the point where the system is noTable to operate any longer. The variation values of real power with the value of load are plotted as the nose curve ¹⁰⁾. The system load flow analysis is performed using PSS®E and the resulting nose curves are plotted using Microsoft Excel. The load flow study is normally performed during planning stage to test the results against the grid planning and operation criteria.

2. Transmission expansion planning problem

Transmission network expansion planning is an important part of power system planning with the objective of acquiring the most optimal plan for the network expansion. The transmission network expansion planning problem consists of finding new transmission lines which can be constructed to deliver power to load centers in efficient and reliable manner from the power nodes ^{8,11)}. The added transmission lines increase the investment costs. The main objective of the transmission expansion is to minimize the total investment cost, maximize benefits subject to satisfying the technical constraints of the transmission network. The objective function is:

$$\text{minimize } \sum_{(i,j)}^n C_{ij} x_{ij} \quad (1)$$

subject to

$$PG_{ref,i} - PG_i = 0 \quad (2)$$

$$PL_{ref,i} - PL_i = 0 \quad (3)$$

$$QL_{ref,i} - QL_i = 0 \quad (4)$$

$$0.98 \leq V_i \leq 1.02 \quad (5)$$

where,

$$P_i = \sum_{j=1}^N [G(x_{ij})e_i e_j - B(x_{ij})e_i f_j + G(x_{ij})f_i f_j + B(x_{ij})f_i e_j]$$

$$Q_i = \sum_{j=1}^N [G(x_{ij})f_i e_j - B(x_{ij})f_i f_j - G(x_{ij})e_i f_j - B(x_{ij})e_i e_j]$$

i, j = Transmission line nodes

x_{ij} = Building parallel line from node i to node j

$G(x_{ij})$ and $B(x_{ij})$ are function of parameter x_{ij}

$V_i = e_i + jf_i$

V_i = Voltage at bus i

PG_i = Generated power at bus i

PL_i = Load real power at bus i

QL_i = Load ractive power at bus i

The objective function represents the investment cost. The constraint in equations 2,3 and 4 represents the conservation of power in each node. The constraints in equation 5 refers to voltage limits. The real and reactive power at each node is expressed in terms of bus voltage ¹²⁾.

3. Voltage stability index by nose curve description

The nose curves indicate the relationship between voltage and active power of the system. This gives the available amount of active power margin before the point of voltage collapse. The voltage of the bus is monitored against the changes in real power consumption. As the load is increased voltage decreases and reaches a nose point, any further increase in load causes instability of the system ^{4,10)}. When the active power is increased the voltage drops due to increase of load admittance. Hence, nose curve identifies the maximum load that can be supplied by the system and the resulting critical voltage.

Consider a simple system consisting of source with voltage $V_s \angle 0$ and load at voltage $V_r \angle \delta$ fed by an infinite bus transmission system as shown in Fig. 1. The resistance of the transmission line connecting the source and the load is small and is neglected, real and reactive powers are given by the equations 6 and 7 ^{10,13)}.

$$P = V_r I \cos \theta = \frac{V_s V_r}{X} \sin \delta \quad (6)$$

$$Q = V_r I \sin \theta = \frac{V_s V_r}{X} \cos \delta - \frac{V_r^2}{X} \quad (7)$$

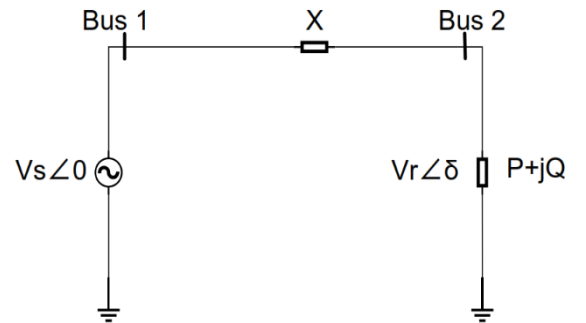


Fig. 1 Simple power system network.

Combining equation 6 and 7 using trigonometric identity $\cos^2 \delta + \sin^2 \delta = 1$ to eliminate the load angle ¹³⁾.

$$\left(\frac{V_s V_r}{X}\right)^2 = P^2 + \left(Q + \frac{V_r^2}{X}\right)^2$$

$$P^2 = \left(\frac{V_s V_r}{X}\right)^2 - \left(Q + \frac{V_r^2}{X}\right)^2$$

$$P = \sqrt{\left(\frac{V_s V_r}{X}\right)^2 - \left(Q + \frac{V_r^2}{X}\right)^2}$$

Considering resistive load, then $Q = 0$ the equation can more be simplified.

$$P = \sqrt{\left(\frac{V_s V_r}{X}\right)^2 - \left(\frac{V_R^2}{X}\right)^2} \quad (8)$$

The relationship in equation 8 is the nose curve equation which relates various power system parameters. A plot of V against P is shown in Fig. 2¹⁴⁾. To each point P , there are two solutions for voltage, one is sTable solution, and the other one is unsTable solution¹¹⁾. In normal operation of any power system in stability region is limited to the upper part of the curve. In addition, normal loading margin P_{margin} between the maximum permissible demand and the nose is usually used as static voltage stability indicator^{4,10,15)}. The load flow analysis is used to determine the maximum permissible demand by gradually increasing the load until the flow fails to converge. The power system will reach its voltage instability limit when any increase in active or reactive loading demand results in the system operating point crossing the nose of the nose curves. Voltage corresponding to maximum loading point is called as critical voltage.

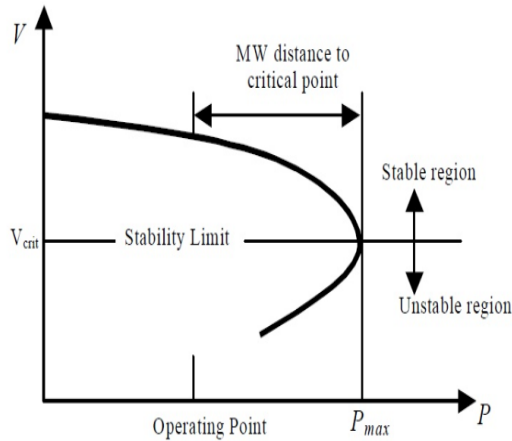


Fig. 2 The P-V curve.

3.1 Evaluation method

The transmission expansion planning focuses on improving the load margin of the network. The system loads increasing, and the transmission networks are operating close to their critical point. The effectiveness of the proposed transmission expansion approach on increasing the load margin while satisfying the system reliability criteria are evaluate against the conventional approach. The load margin at each node is determined. Load margin indicates the distance of the load from the base operating point until the critical point. The load margin can be obtained from the nose curve, and it is calculated as shown in equation 9.

$$\text{Load margin} = P_{\text{critical}} - P_{\text{initial}} \quad (9)$$

P_{initial} is the value of load (MW) at normal operating point and P_{critical} is the value of load (MW) at voltage collapse point. The network base case is modelled, and the

conventional and proposed approaches will be considered for transmission expansion planning. The effectiveness of the approach will be determined. The evaluation method is based on calculating the total system load margin of each approach and their results are compared.

3.2 Base case consideration

In implementing the transmission expansion planning, the base case scenario of the operating grid network is considered. It is modelled in PSS®E for load flow analysis. Fig. 3 shows the single line diagram for the grid network system. The power flow results are given in Table A.1.

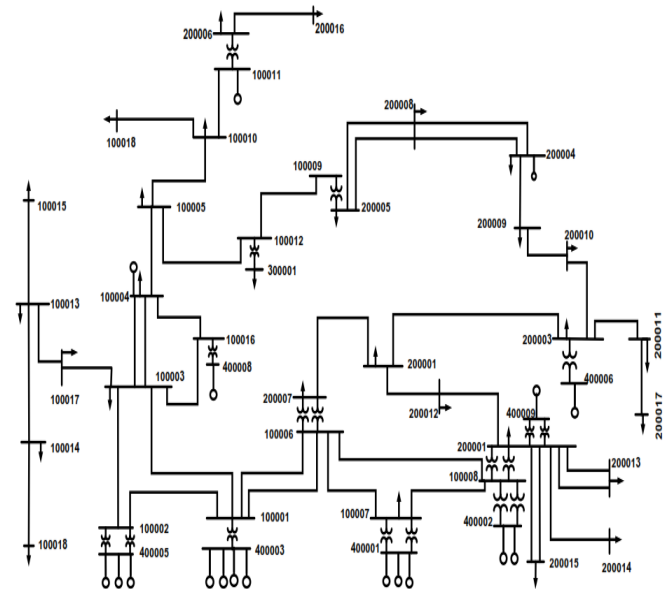


Fig. 3 Base case grid network.

4. Grid network expansion planning by approaches

4.1 Conventional approach

This is a normal transmission expansion planning approach used in optimization problems. The objective is to minimize the investment cost while satisfying the system reliability conditions^{16,17)}. When the power grid is represented by the power flow model, the mathematical model for the transmission expansion planning problem can be formulated as shown in equations 1-5.

The objective function represents the investment cost. The constraint in equations 2,3 and 4 represents the conservation of power in each node. The constraints in equation 5 refers to voltage limits. In obtaining the optimal transmission expansion planning, the grid network is simulated using PSS®E and the simulation results are tested against the objective function as well as the constraints inequalities. The simulation result is given in appendix A in Table A.1.

4.2 Conventional approach results

The optimal solution for this network when the AC model is used is given in Table 1. Only seven new transmission lines have been identified for new circuit addition. The circuits for reinforcements are 100007-100020, 200002-200003, 200002-200012, 200003-200010, 200003-200011, 200004-200009 and 200009-200010.

Table 1 Conventional approach results.

S/N	Transmission line	Cost [\$]	Project status
1	100003-100017	29640000	0
2	100006-100007	39216000	0
3	100007-100008	3420000	0
4	100013-100015	34587600	0
5	100013-100017	13748400	0
6	100007-100020	20748000	1
7	200001-200012	8540000	0
8	200002-200003	30625000	1
9	200002-200012	8435000	1
10	200003-200010	12897500	1
11	200003-200011	9275000	1
12	200004-200009	17850000	1
13	200009-200010	19180000	1
14	200011-200017	9275000	0

The results of the proposed transmission lines are indicated in the Fig. 4 below as dotted lines.

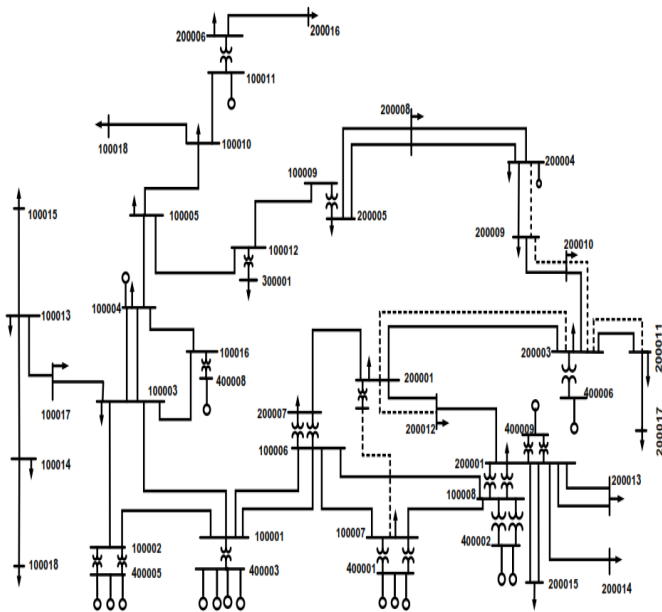


Fig. 4 Conventional approach network results.

The conventional approach in transmission expansion planning does not consider the voltage and active load power complexity towards voltage collapse point. The rate of voltage decline towards critical point is a sensitive constraint in

transmission planning. In determining the transmission network configuration, the conventional approach is modified to consider the the relationship of voltage and active power in the system as a planning constraint.

4.3 Modified conventional approach

The proposed approach objective is to minimize the investment cost while satisfying the system reliability conditions. The nose curve is considered in this approach to calculate the nose curve index. The index is used as one of the constraints in transmission expansion planning optimization. The mathematical model for the transmission expansion planning problem is reformulated to include the the nose curve index constraint. The optimization is calculated using equations 1-5 and the nose curve index constraint is given by equation 10.

$$\left(\frac{V_i - V_{cr}}{P_L}\right) < 0.01 \quad (10)$$

The constraint in equations 10 represents the nose curve index at a particular node in the power system where V_{cr} is the critical bus voltage in pu. The nose curves show the relationship between the power injection and the corresponding change in voltage at a particular bus. The nose curves give the values of voltage stability margin and load margin as shown in Fig. 5 which is a crucial information for the transmission planning. These curves are used to calculate the voltage indices which show the rate of voltage decline with respect to the increment of the real load power. The index considers the nonlinear characteristics of the system and its voltage limits.

The higher the nose curve index the weaker the bus towards voltage collapse and vice versa. When the voltage index becomes large, the system turns insecure and ultimately collapses. The indices for the existing network are shown in Table 2.

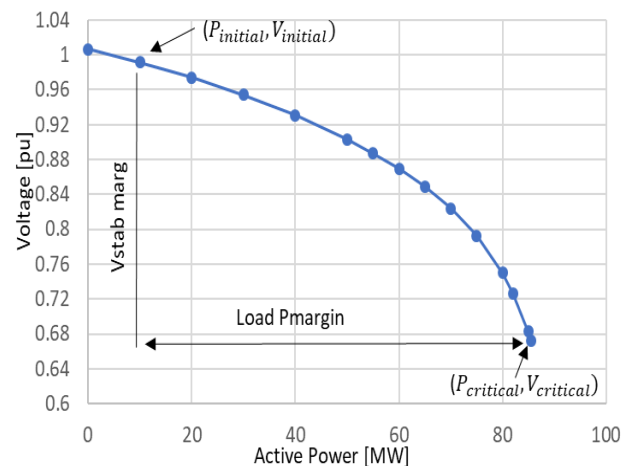


Fig. 5 Nose curve diagram.

Table 2 Nose curve index results.

Bus	Name	$\left(\frac{V_i - V_{cr}}{P_L}\right)$
200017	Tanga	0.0239
200003	Hale	0.0312
200009	Same	0.0424
200012	Mlandizi	0.0123
100017	Mufindi	0.0096
200002	Chalinze	0.0241
200011	Maweni	0.0308
200010	Kasiga	0.0256
100015	Mbeya	0.0024

The transmission expansion planning optimal solution in this approach is obtained by undertaking load flow study of the modeled network using PSS®E and the simulation results are tested against the objective function as well as the given constraints inequalities. The simulation results are given in appendix A in Table A.1.

4.4 Proposed approach results

In this approach, the optimal solution for transmission expansion planning is given in Table 3. Only nine new transmission lines have been identified for new circuit addition. The circuits for reinforcements are 100007-100020, 200002-200003, 200001-200012, 200002-200012, 200003-200010, 200002-200012, 200003-200011, 200004-200009 and 200009-200010.

The results of the proposed transmission lines are indicated in the Fig. 6 as dotted lines.

Table 3 Proposed approach expansion results.

S/N	Transmission line	Cost [\$]	Project status
1	100003-100017	29640000	0
2	200011-200017	9275000	1
3	100006-100007	39216000	0
4	100007-100008	3420000	0
5	200009-200010	19180000	1
6	100013-100015	34587600	0
7	100013-100017	13748400	0
8	100007-100020	20748000	1
9	200001-200012	8540000	1
10	200002-200003	30625000	1
11	200002-200012	8435000	1
12	200003-200010	12897500	1
13	200003-200011	9275000	1
14	200004-200009	17850000	1

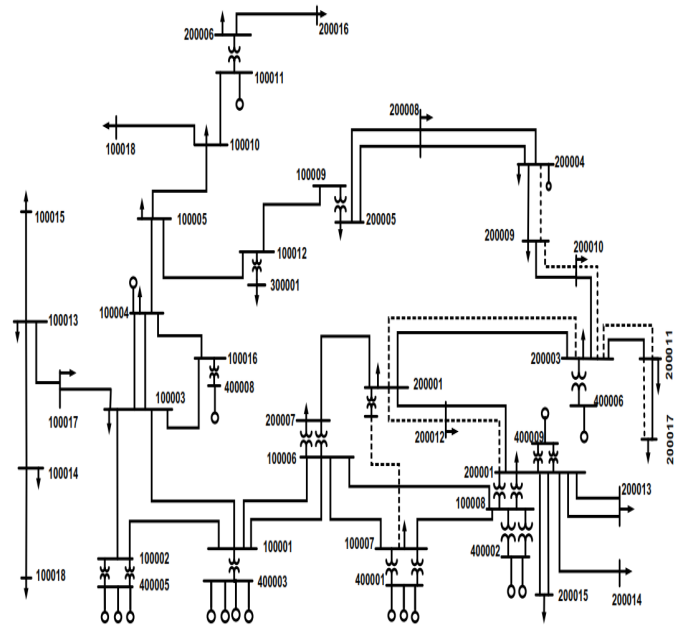


Fig. 6 Expansion planning results by proposed approach.

4.5 Consideration by comparison

The conventional approach and proposed approach are evaluated to determine the effectiveness of the approach. The evaluation method is based calculating the total system load margin of each approach and their results are compared. The results are given in Table 4. The results from Table 4 shows that the proposed approach which considers the nose curve index gives 1685MW load margin increase compared to 1596MW load margin provided by the conventional approach. The difference of 85MW is quite significant for voltage stability improvement in constrained transmission network.

Table 4 Calculated load margin at each node.

Bus	Load margin [MW]		
	Base	Conventional	Proposed
200017	73	103	133
200003	116	184	187
200009	80	136	137
200012	230	327	364
100017	121	130	130
200002	234	355	369
200011	94	156	159
200010	82	137	138
100015	66	68	68
$\sum_{i=1}^N (\text{Load margin})$	1096	1596	1685

The transmission network expansion planning focuses on the improvement of voltage stability of the power system. The proposed approach which considers the nose curve index in its analysis provides an expansion plan with high voltage stability compared to the conventional approach. This is because of the nose curves index which determines the most critical bus to voltage collapse, thus determining the weak nodes in the system as shown in Table 2. The simulation result of the proposed approach is shown in Table A.1 with significant voltage improvement. This information is very crucial for the system planner to make decision on the location of new transmission line connecting the weak bus to other busbars for system reinforcement. Table A.1 in appendix A indicates the resulting voltages obtained when the conventional and proposed approaches are considered in expansion planning. The number of transmission lines to be added, the load margin improvement and their associated costs are shown in Table 5.

Table 5 Approaches comparison.

Approach	Added lines	Load margin [MW]	Cost [\$]
Conventional	7	1596	119,010,500
Proposed	9	1685	136,825,500

The proposed approach which considers the nose curve index is an effective tool in transmission expansion planning. The solution which satisfies the index, its transmission network configuration gives high system voltage stability. The solutions which do not satisfy the index inequality; have high nose curve indices, are subjected to voltage instability. They are operating close to the voltage collapse point.

5. Conclusion

The increase of power demand has caused the system to be complex and sensitive to voltage fluctuations. The system experiences voltage instability, line overloading and power system blackouts. The relationship between the load power and the voltage in the power system is very important in transmission expansion planning. There are various approaches deployed to implement the transmission expansion planning optimization.

This paper proposed the simplified approach which considers the nose curve index as a planning tool based on some voltage stability criteria. The voltage stability margin

and load power margin increase obtained from the nose curve form a basis for nose curve index calculation. The analysis and consideration performed in this paper has successfully indicated that the proposed approach gives better load margin improvement, and the resulting voltage profile shows significant compliance to the transmission network expansion planning constraints. It is very important to calculate the nose curve index values. This is because accurate nose curve index values are important to determine the capacity and location of transmission line to be added to the existing network.

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Appendix A

The load flow simulation is performed using PSS®E for the base case scenario, conventional and proposed approaches. The results are compared against the planning criteria to get the effectiveness transmission network configuration.

Table A.1 Simulation results comparison (Vp.u).

Bus	Base	Conventional	Proposed
100001	1.0346	1.0373	1.0274
100002	1.0347	1.0355	1.0256
100003	1.0485	1.0534	1.0317
100004	1.0546	1.0622	1.0306
100005	1.0226	1.0365	1.0271
100006	1.0145	1.0201	1.0204
100007	0.9916	0.9935	0.9938
100008	0.9862	0.9873	0.9876
100009	0.9831	1.0028	1.0039
100010	1.0165	1.0197	1.0198
100012	0.9832	1.0029	1.0040
100013	1.0203	1.0274	1.0277
100014	1.0399	1.0472	1.0476
100015	0.9713	0.9790	0.9794
100016	1.0503	1.0546	1.0248
100017	1.0246	1.0311	1.0214
100018	1.0417	1.0491	1.0295
100019	1.0046	1.0079	1.0080
100020	0.9990	0.9977	0.9987
200001	0.9501	0.9992	1.0001
200002	0.9680	1.0048	1.0063
200003	0.9987	1.0114	1.0138
200005	0.9559	0.9763	0.9777
200006	1.0012	1.0012	1.0012
200007	1.0018	1.0107	1.0110
200008	0.9559	0.9763	0.9777
200009	0.9661	0.9927	0.9948
200010	0.9661	0.9928	0.9949
200011	0.9803	1.0034	1.0075
200012	0.9474	0.9961	0.9984
200013	0.9450	0.9944	0.9953
200014	0.9439	0.9934	0.9942
200015	0.9386	0.9884	0.9892
200016	0.9800	0.9800	0.9800
200017	0.9676	0.9910	1.0023
300001	0.9761	0.9960	0.9971