International Journal of Energy Production and Management
Vol. 10, No. 1, March, 2025, pp. 145-152
Journal homepage: http://iieta.org/journals/ijepm

Transmission Line Expansion Planning in a Deregulated Environment

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https://doi.org/10.18280/ijepm.100114

Received: 10 November 2024
Revised: 5 February 2025
Accepted: 18 March 2025
Available online: 31 March 2025

Keywords:
cost benefit analysis, high temperature low sag conductor, right of way challenge, transmission expansion planning

ABSTRACT

India's power sector is witnessing unprecedented growth, driving the need for increased generation capacity. To support this demand, a robust and efficient transmission system is essential. As the construction of new transmission lines becomes more frequent, it is vital to optimize their design to remain profitable in a deregulated market. This paper presents a cutting-edge method for optimal transmission expansion planning, utilizing the MW-KM method and a Cost/Benefit index for enhanced optimization. The proposed approach effectively identifies the most economically viable expansion strategies. Additionally, the paper explores the use of High Temperature Low Sag (HTLS) conductors as a strategic solution in scenarios where traditional methods are either costly or hindered by Right of Way challenges (RoW). This holistic approach ensures that India's growing energy needs are met with both efficiency and cost-effectiveness. In this paper, a case study on the 5-bus system test system carried out and income of each line calculated on MW-KM method, the number of new transmission lines required is decreased to three from seven by using cost benefit analysis and increased the avg line revenue of the system by 25%. The RoW issues of the planned system successfully addressed in this paper.

1. INTRODUCTION

India's economic growth and rapid urbanization have led to a significant increase in energy demand, with electricity consumption witnessing a compound annual growth rate (CAGR) of 4.1% over the from 2011 to 2020. India's power sector is undergoing significant transformation, driven by rapid urbanization, industrialization, and a corresponding surge in electricity demand. Looking ahead, the 20th Electric Power Survey (EPS) projects an even steeper rise, with electricity demand expected to grow at a CAGR of 7.18% over the next five years. To meet this growing demand, not only is there a need to expand generation capacity, but also to ensure that the transmission infrastructure can effectively deliver power across vast distances. The deregulation of power system introduced the concept of 'Open Access' in transmission, which mandates the unbiased and non-discriminatory use of transmission lines and associated facilities by any licensee or entity involved in power generation and distribution [1]. While this provision has promoted economic power transmission and facilitated the development of a competitive electricity market [2], it has also introduced new challenges related to system security and operational reliability [3]. In this deregulated environment, efficient transmission pricing is crucial to maintaining revenue gains and providing the right economic signals for the optimal use of transmission resources and future investments. However, as the demand for electricity continues to rise, and generation capacity expands to meet this demand, the transmission system's capacity must also increase. The traditional approach is construction of new lines which are loaded more than 80%. The 20% of margin is kept in the planning because to meet unpredictable delay of the new line commissioning. This technique is not suitable in deregulation environment. So, optimization technique is developed in this paper to reduce required number of new lines. Yet, securing the Right of Way (RoW) for these new lines has become increasingly challenging due to urbanization, escalating costs, and public opposition to new overhead lines [4]. To address these challenges, there is a growing need to enhance the capacity of existing transmission systems without expanding the physical infrastructure. One effective solution involves the replacement of conventional ACSR conductors with High Temperature Low Sag (HTLS) conductors. HTLS conductors can operate at higher temperatures and carry more current than Aluminum Conductor Steel-Reinforced (ACSR) conductors, making them ideal for increasing transmission capacity within existing RoW constraints. However, it is important to ensure that the existing transmission towers are in good condition and that the hardware, clamps, and equipment connected to these lines can support the higher ampacity [5]. This paper explores the application of HTLS conductors as a strategic alternative in transmission expansion planning. By replacing ACSR conductors with HTLS conductors in areas where transmission constraints are evident, it is possible to increase capacity and improve system efficiency without the need for new transmission lines. The study considers a five-bus system with a uniform 20% load growth, analysing scenarios where new lines are added as per conventional method, and the

Cost/Benefit of these expansions is evaluated and utilized for optimization of transmission expansion. The findings demonstrate that using HTLS conductors can effectively meet India's growing energy needs while navigating the complexities of a deregulated power market and overcoming RoW challenges [6].

In the Section 3 the developed methodology for transmission expansion including RoW constrains is explained. During the expansion planning system is considered as in acceptable limits if all the bus voltages are within 10% of violation, active and reactive power generation is within range of minimum-maximum generators range. In this paper all the load flow solution are obtained by using N-R load flow solution method in PSSE software and case study done on IEEE 5-bus system with results are discussed in Section 4 [4, 6].

The outline of the research is to reduce the number of transmission lines based on revenue generation and addressing the RoW issue during transmission line planning.

2. LITERATURE REVIEW

The evolution and optimization of transmission expansion planning in deregulated environments have been extensively explored in recent literature. The regulatory framework plays a crucial role in transmission planning, as underscored by the Indian Electricity Act of 2003 [1]. The open access concept paper by Central Electricity Authority (CEA) explained basis of open access system, existing pricing, open access pricing and energy accounting [2]. Fang and Hill [3] proposed a novel strategy tailored for competitive electricity markets, emphasizing the importance of security-constrained planning models in maintaining system stability. The CEA's recent manual on transmission planning criteria [4] offers updated methodologies for handling the complexities of modern power systems. This legislation, combined with guidelines from the Central Electricity Authority (CEA) [5], has provided a structured approach to the rational use of high-performance conductors and open access in inter-state transmission. Kaur et al. [6] developed an analytical approach for optimal transmission expansion planning under deregulation, highlighting the challenges of balancing efficiency and reliability. Deregulation in India has introduced significant shifts in the power sector, as detailed by Raikar and Jagtap [7]. Their work provides an overview of the current scenario and future prospects, focusing on the impact of policy changes on transmission planning. Zhang et al. [8] extended this discussion by introducing a mixed-integer programming model for security-constrained transmission planning, which they found to be effective in managing the competitive dynamics of deregulated markets. Real-time pricing and its implications for residential electricity consumers have been explored by Aubin et al. [9]. Their econometric analysis provides insights into the challenges of implementing real-time pricing models in residential settings. Additionally, Salyani and Salehi [10] examined transmission and distribution reliability from a customer-oriented perspective, offering a methodology that prioritizes consumer satisfaction. Andersson's [11] work on the dynamics and control of electric power systems has been foundational, particularly in the context of power system stability and control, as explored in his contributions to the IEEE Press. Wood et al. [12] furthered this discussion in their textbook on power generation, operation, and control, which remains a key reference for understanding the operational aspects of power systems. The role of software tools in power system analysis has gained attention with Milano's development of a Python-based tool [13], which has been instrumental in advancing computational methods in power system studies. Distributed generation, as defined by Ackermann et al. [14], has also emerged as a critical area of research, particularly in terms of its integration into existing power systems. Voltage stability and enhancement through optimal placement of Static Var Compensators (SVC) have been investigated by Thukaram and Lomi [15], who demonstrated the effectiveness of SVCs in improving both static and transient voltage stability. Saadat [16] provided a comprehensive analysis of power systems, offering detailed methodologies for addressing stability and control issues. The competitive nature of modern electricity markets necessitates innovative approaches to transmission planning. Meliopoulos et al. [17] proposed a new methodology that accounts for market dynamics, while Nabavi-Niaki and Iravani [18] focused on the steady-state and dynamic modeling of Unified Power Flow Controllers (UPFC), crucial for maintaining power system flexibility. Christie et al. [19] addressed the broader challenges of transmission management in deregulated environments, emphasizing the need for robust frameworks to handle the complexities introduced by market liberalization. Przysucha et al. [20] explored the application of Monte Carlo simulations in short-term demand forecasting, providing a statistical approach to handling uncertainty in power system operations. Finally, Buygi et al. [21] made a review of the presented approaches, along with a discussion of their advantages and drawbacks, facilitates the introduction of new methods and criteria for transmission expansion planning in a deregulated environment. Bresesti et al. [22] proposed a new transmission expansion strategy has been developed to effectively manage future generation and load patterns in a competitive market environment. Tachikawa et al. [23] presented a method is presented for evaluating the maximum power that can be injected at a bus and identifying transmission lines that may become bottlenecks under uncertain conditions. Le et al. [24] used applied neural network for short term load forecast and proposed advance methods for optimization of data used for load forecast. Mahle [25] explained the non-conventional energy sources development in the country USA.

In the literature survey it is concluded that to meet the future load growth the conventional and non-conventional energy sources expansion will be done and it is necessary to increase the transmission infrastructure to connect generators and distributors. This load growth can be calculated using short term and long-term load forecast techniques. In conventional method to expand the transmission capacity simply new lines are added where lines are loaded more than 80%. Due to open access and deregulation of transmission system the private entities can operate, construct, and transport the power, due to conventional method the operators won't show interest to participate in transmission operation due to low gain or loss. So, in this paper a methodology is developed to reduce number of transmission lines with cost benefit index using MW-KM method and addressed how to overcome the RoW issues with high power conductors During this methodology implementation it is necessary to check whether the system conditions are in acceptable limits or not. The system is said in acceptable limits if the Voltage violations are withing 10% of range, generators should generate power within limits and all the transmission lines are loaded under 80% of capacity.

3. METHODOLOGY

3.1 Initial load flow analysis

The objective of the initial phase is to assess the current performance of the five-bus system and ensure that all parameters were within acceptable limits. Following the analysis, it is essential to verify that all critical system parameters including voltages, generation limits and power flows met the specified criteria for acceptable performance.

3.2 Load increase and line identification

The objective of this phase is to evaluate the impact of a 20% load increase on the five-bus system and identify any additional transmission lines needed to maintain system performance. The process began with increasing the load at all buses by 20%. Subsequently, a load flow analysis is to be re-run to assess the effects of this increased load on the system. Based on the results, new transmission lines were identified as required to ensure that the system remains within acceptable limits, adhering to 80% loading criteria for the existing lines and voltages at all the busses are less than or equal to 10% of violations.

3.3 Addition of new lines

The objective of this phase is to integrate the newly identified transmission lines into the five-bus system and reassess its performance. This process involves incorporating the new lines into the system and then conducting a load flow analysis to evaluate the impact of these additions. The goal is to ensure that all system parameters including voltages, power Transmission Line limits and generation limits remains within acceptable limits after the integration of the new transmission lines.

This is conventional technique following presently to meet load growth but in deregulation environment to improve the revenue of the operator's, the optimization transmission network is necessary and in this paper this technique is explained in further steps.

3.4 Cost/Benefit analysis

The objective was to evaluate the economic feasibility of each transmission line using the Cost/Benefit Index (C_x). To achieve this, the following steps were performed:

3.4(a): Calculate the Cost/Benefit Index (C_x) for each transmission line is shown in Eq. (1) and average C_x of the system shown in Eq. (2).

$$Cx = \frac{Income}{Cost} = \frac{Pi * Di * TSC}{Ci}$$
$$Cx = \frac{Pi * Di * TSC}{CKM * Di} = \frac{Pi * TSC}{CKM} \quad (1)$$
(assumed TSC =1)

$$\text{Avg } Cx = \frac{\text{Sum of Cx of individua llines}}{\text{total no of lines}}$$
$$Avg\ Cx = \sum_{i=1}^{n} \frac{Cxi}{n} \quad (2)$$

3.4(b): Rank the transmission lines based on their C_x values from highest to lowest.

This C_x index represent the revenue of transmission line, High C_x means line revenue is high and low C_x means line revenue is low.

3.5 Optimization of transmission network

Due to addition of the new transmission lines the system performance improves with improvement of voltage profile; reduction of line losses and voltage drops. So, we can remove some of added new transmission line. The objective was to optimize the transmission line network by removing newly added transmission lines with the lowest Cost/Benefit Index (C_x) values. To achieve this, transmission lines with the lowest C_x values were systematically removed from the planning by following below steps.

3.5(a): Remove the low C_x transmission line from the system

3.5(b): Run the load flow analysis of modified network.

3.5(c): Check whether all the voltages are within limits and all the transmission lines are loaded within 80% and stability condition. If all the conditions are satisfied then step 3.4, if not go to step 3.5(d).

3.5(d): Keep the removed line in the planning and next low C_x line will be removed from network and go to step 3.5(b).

This process was continued iteratively until the remaining lines in the network ensured overall system stability and reliability.

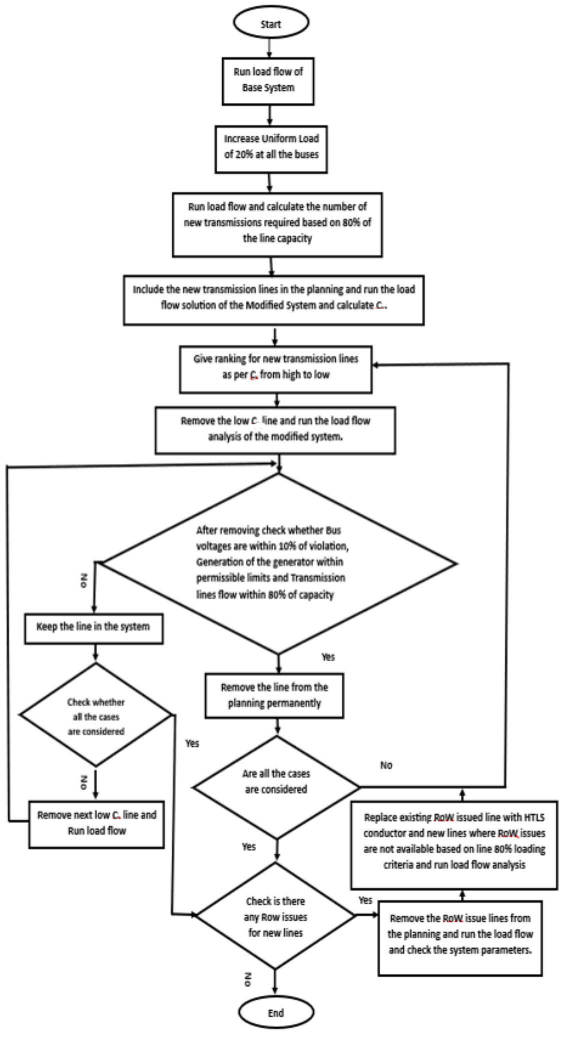

Figure 1. Flow chart of methodology

3.6 High power conductor

In planning of transmission lines expansion RoW issues are not considering. But in this paper RoW challenges are considering and advance high-power conductors are used. If any line expansion is not possible with RoW constrains, they were replaced HTLS conductors to meet load growth. Finally, a comprehensive load flow study was conducted to ensure that all system parameters remained within acceptable limits, confirming the effectiveness of the adjustments made.

3.7 Compliance check

The objective was to ensure that the final transmission system adhered to all regulatory standards. This involved verifying that each step of the process, from initial analysis to final adjustments, complied with the rules set forth by the Central Electricity Authority (CEA). Figure 1 illustrates the flow chart of the developed methodology.

4. CASE STUDY RESULTS AND DISCUSSION

Initial load flow analysis results: The initial load flow analysis is solved by N-R load flow solutions using PSSE software. With the initial data of the IEEE 5-bus test system [26] demonstrated that all system parameters, including voltages (within 10% violations) and generation is within generator limits and results are shown in Tables 1-3 and Figure 2.

Table 1. Initial data of the five-bus system

Bus Number	Voltage (p.u.)	Pload (MW)	Qload (Mvar)	Type
1	1.06	-	-	Swing Bus
2	1	20	10	Load Bus
3	1	45	15	Load Bus
4	1	40	5	Load Bus
5	1	60	10	Load Bus

Table 2. Transmission data of the five-bus system

From Bus	To Bus	Line R (p.u)	Line X (p.u)	Charging B (p.u)	Rating (I as MVA)
1	2	0.02	0.06	0.06	170
1	3	0.08	0.24	0.05	65
2	3	0.06	0.18	0.04	32
2	4	0.06	0.18	0.04	32
2	5	0.04	0.12	0.03	72
3	4	0.01	0.03	0.02	32
4	5	0.08	0.24	0.05	12

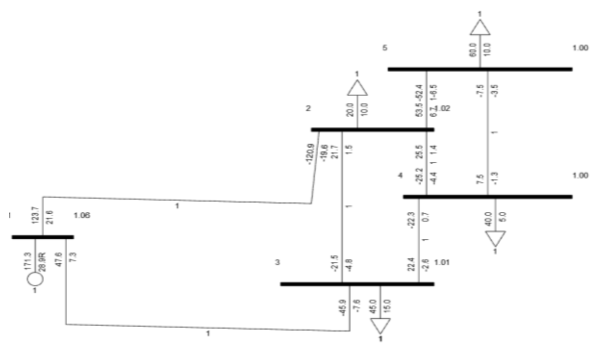

Figure 2. Initial load flow result of test bus system

Table 3. Generator outputs of initial five-bus system

Bus Number	P_{Gen} (MW)	P_{Max} (MW)	P_{Min} (MW)	Q_{Gen} (Mvar)	Q_{Max} (Mvar)	Q_{Min} (Mvar)
1	171.31	300	40	28.87	120	-60

Load increase and line requirements: In this paper assumed the future extreme load forecast after 3 years as 20% at all buses. To meet future load demand is required the addition of new transmission lines to accommodate the increased demand. The analysis indicated the specific lines needed based on 80% loading criteria. The Voltages and angle after load addition shown in Table 4 and number of new lines required is shown in Table 5.

Table 4. Generator outputs of initial five-bus system

Bus Number	Voltage (p.u.)	Angle (°)
1	1.0600	0.00
2	1.0130	-4.40
3	0.9892	-6.92
4	0.9869	-7.40
5	0.9760	-8.62

Table 5. New line requirements after load addition

Line	Line Limits (MVA)	% Loading	Existing Lines	Total Required	New Lines Needed
1-2	170	85	1	2	1
1-3	65	86	1	2	1
2-3	32	81	1	2	1
2-4	32	96	1	2	1
2-5	72	90	1	2	1
3-4	32	85	1	2	1
4-5	12	83	1	2	1

Addition of new lines: Post addition of transmission lines, the parameters of the system are placed in Table 6 and Table 7. As per these tables it is concluded that the post addition of new transmission lines, In the post line addition results it is concluded that all the bus voltages are within 10% of violations and all the transmission lines are loaded within 80% of capacity, P_g and Q_g values are within generation limit and system in stability condition. It is observed post-addition of transmission lines the system performance is improved i.e.; bus voltages are improved and line losses are decreased.

Table 6. Post-addition load flow analysis results

Bus Number	Voltage (p.u.)	Angle (°)
1	1.06	0
2	1.05	-2.23
3	1.04	-3.44
4	1.04	-3.67
5	1.03	-4.22

Table 7. Post-addition transmission line flows

Line	Line Limits in MVA	% Loading	Active Power Flow (p.u.)
1-2	170	41	0.73
1-3	65	41	0.281
2-3	32	39	0.13
2-4	32	46	0.152
2-5	72	42	0.319
3-4	32	42	0.134
4-5	12	45	0.045

As per conventional method total lines to be added is seven but in further steps using optimization techniques total number of lines to be added will be reduced.

Cost/Benefit analysis: The Cost/Benefit Index (Cx) analysis provided a clear ranking of transmission lines based on their economic feasibility. Lines with the highest Cx values were prioritized. This C_x and average C_x are calculated using Eqs. (1) and (2) and these values are shown in Table 8.

Table 8. Cost/Benefit analysis results

Line	No of Lines	Income of the Line in Cr. for Year	Construction Cost in Cr. for KM	C_x	C_x Ranking
1-2	2	63.95	1.5	42.63	1
1-3	2	24.62	1	24.62	3
2-3	2	11.39	0.8	14.24	6
2-4	2	13.32	0.8	16.64	4
2-5	2	27.94	0.9	31.05	2
3-4	2	11.74	0.8	14.67	5
4-5	2	3.94	0.6	6.57	7
Average Cx: 21.49					

In the Table 8, income indicates the income of respective line, construction cost/KM indicates the cost for construction of new line for KM.

Optimization of transmission network: In the process of optimization of transmission network the lowest C_x line to be removed and load flow should run to check status of the modified network. In this process the lowest C_x valued line 4-5 removed and system status is checked and system parameters are placed in Table 9 and Table 10 and as per results the system is in acceptable limits. as per Table 11, it is observed the average C_x calculated using Eq. (2) and its value of the modified network is increased.

As per Table 11, the low C_x line 2-3 will be removed from the planning and system limits are checked and found satisfactory. So, again C_x table is prepared as per new flows and after removal of line 2-3, the low C_x line removed from the planning.

Table 9. Bus voltages and angles after line 4-5 removal

Bus Number	Voltage (p.u.)	Angle (°)
1	1.0600	0.00
2	1.0439	-2.23
3	1.0352	-3.38
4	1.0344	-3.58
5	1.0273	-4.29

Table 10. Transmission line flows after line 4-5 removal

Line	Line Limits in MVA	% Loading
1-2	170	41
1-3	65	41
2-3	32	39
2-4	32	46
2-5	72	42
3-4	32	42
4-5	12	45

Table 11. Cost/Benefit analysis results after removing line 4-5

Line	No of Lines	Income of the Line in Cr. for Year	Construction Cost in Cr. for Km	C_x	C_x Ranking
1-2	2	64.30	1.5	42.87	1
1-3	2	24.35	1	24.35	3
2-3	2	10.86	0.8	13.58	6
2-4	2	12.70	0.8	15.88	4
2-5	2	29.35	0.9	32.61	2
3-4	2	10.95	0.8	13.69	5
4-5	1	5.08	0.6	8.47	
Average Cx: 22.65					

Table 12. Results of five bus test system without HTLS conductor

Case Study	Lines	Initial Average C_x	Average C_x after Case Study	Remarks
Case 1	4-5 removal	21.49	22.65	After low C_x line 4-5 removal, system conditions are within limits.
Case 2	2-3 removal	22.65	23.58	After case-1, the low C_x line 2-3 removal, the system conditions are within limits.
Case 3	3-4 removal	23.58	25.59	After case-2, the low C_x 3–4-line removal, the system conditions are within limits.
Case 4	2-4 removal	25.59	28.24	After case-3, low the C_x line 2-4 removal, the system conditions are within limits.
Case 5	1-3 removal	28.24	28.24	After case-4, the low C_x line 1-3 removal, the system conditions are not within limit. So, line 1-3 kept in the planning and next low C_x 2-5 line removed from the planning.
Case 6	2-5 removal	28.24	28.24	After line 2-5 removal, the system conditions are not within limits. So, line 2-5 kept in the planning and the next low C_x line 1-2 removed from the planning.
Case 7	1-2 removal	28.24	28.24	After case-4, the next low C_x 1-2 removal, the system conditions are not within limits. So, line 1-2 kept in the planning

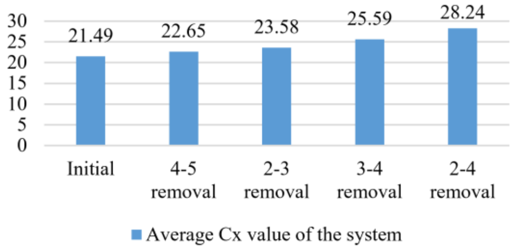

Figure 3. Average C_x of the five-bus system

This process is continued and planning results for the test system are shown in Table 12 and Figure 3. So, using optimization techniques total number of new lines required are reduced to three from seven. So, total line requirement reduced to 43% of conventional method.

High power conductor: Addressing RoW issues (line 1-3,2-3,2-4 had RoW issues) and expansion of line 1-3 is not possible. To overcome with single 1-3 load flow analysis done. In results line 2-3 and 2-4 are loading more than 80% and due to RoW issues expansion of line 2-3 and 2-4 is not possible. So due to RoW issues of lines 2-3 and 2-4, these 2-3 and 2-4 lines are replaced with HTLS conductors. The results of the above system shown in Table 13 and Table 14. During calculation of C_x it is necessarily require to construction cost of the upgraded lines (with HTLS conductor).

All the parameters of the final load flow results are shown in Table 13 and Table 14 and found that all the critical parameters are within limits. Final planning results are shown in Table 15 and average Cx value shown in Figure 4.

Table 13. Bus voltages and angles after line 4-5 removal

Bus Number	Voltage (p.u.)	Angle (°)
1	1.06	0
2	1.0382	-2.39
3	1.0135	-4.98
4	1.0132	-5.24
5	1.0182	-4.78

Table 14. Line flow study results of test system with HTLS conductor

Line	% Loading	No of Lines	C_x Value
1-2	39	2	47.36
1-3	46	1	36.53
2-3	56	1	24.70
2-4	69	1	26.80
2-5	48	2	33.64
3-4	80	1	15.44
4-5	23	1	5.40
Average C_x :30.10			

Table 15. The final results of transmission expansion planning

Line	Existing No of Lines	New Lines to be Added	Initial C_x	Final C_x	HTLS Conductor Used
1-2	1	1	42.63	47.36	No
1-3	1	0	24.62	36.53	No
2-3	1	0	14.24	24.70	Yes
2-4	1	0	16.64	26.81	Yes
2-5	1	1	31.05	33.64	No
3-4	1	0	14.67	15.44	No
4-5	1	0	6.57	5.40	No
	Average C_x		21.49	30.10	

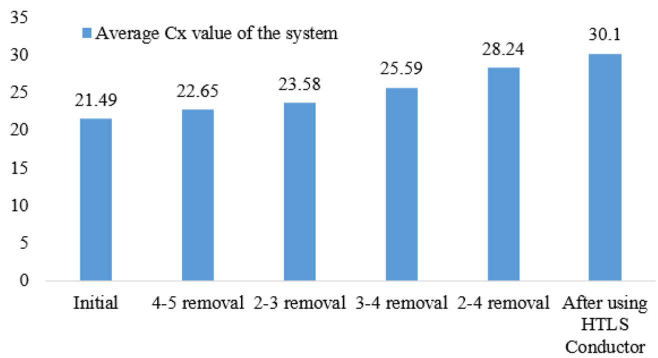

Figure 4. Average Cost/Benefit index after the tests system

From Tables 8, 11, 12 and Figure 3 it is concluded that the average C_x value of the system is improved using Cost/Benefit analysis, which indirectly represent revenue from to the operators of the transmission lines are increased and the require number of transmission lines are reduced and saved the investment cost. From Tables 13-15 and Figure 4, it is concluded that RoW issues are successfully attended and C_x value also improved. This methodology can be applied to the practical system by increasing load as per load forecast techniques and identifying RoW issues and including HTLS conductors in the planning.

5. CONCLUSION

In previous researches and conventional method to meet future load growth new transmission lines are added based on 80%-line capacity and it is equal to seven in this research when load growth is 20% at all the buses of IEEE 5 Bus system. However, by employing the Cost/Benefit Index (C_x) approach, the number of lines required is reduced to three. These three lines are selected based on their higher revenue potential, allowing the system to function effectively with fewer lines by initially eliminating those with lower revenue. This technique led to an increase in the average C_x value from 21.49 to 28.24, representing a 30% rise in revenue per line. In the latest research the HTLS conductor and its strengths are discussed but the research to use HTLS conductors in transmission planning is not up to the mark. In this paper addresses RoW issues and proposes the use of HTLS conductors as an alternative to adding new lines for enhancing transmission capacity. The optimization approach removing economically less favourable lines and integrating HTLS conductors resulted in substantial cost savings and improved system performance. This approach not only increased the system's average C_x value, indicating higher revenue from existing transmission lines, but also effectively resolved RoW issues.

In this paper the transmission lines limits are considered as fixed amps but in the latest research Dynamic Line Loading are implementing. If we implement Dynamic line loading in addition to this methodology further it reduced the number of transmission lines required. The (n-1) contingency analysis is not done. There is a future scope to implement this methodology along with (n-1) and Dynamic Line Loading gives most accurate and optimization results.

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NOMENCLATURE

C_i	Cost of alternative line in Cr
C_{KM}	Construction cost of line per km in Cr
C_x	Cost/Benefit Index
D_i	Length of transmission line in km
HTLS	High tension low sag conductor
MW-KM	Mega watt per Killo meter
P_i	Real power flow in MW or p.u.
TSC	Transmission service charges in Rs./KW/kM/hour
n	Total no of Transmission line
P_g	Generated active power at generating plant in MW or p.u.
P_{max}	Maximum Generator Active Power limit in MW or p.u.
P_{min}	Minimum Generator active power limit in MW or p.u.
Q_g	Generated reactive power at generating plant in MVAr or p.u.
Q_{max}	Maximum Generator Reactive Power limit in MVAr or p.u.
Q_{min}	Minimum Generator Reactive power limit in MVAr or p.u.