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Exploring Multi-Objective Transmission Planning for Investment-Constrained Power Systems

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***Abstract*—In power systems comprised of a small number of generators and lines, additional investment significantly affects reliability, debt burden, and operating costs. Wise selection of candidate investments balancing multiple objectives is crucial, especially in developing countries where load shedding may already be in effect. In this work, a static transmission expansion methodology is presented using a multi-objective optimization framework, where investment cost, operating cost, and load shedding cost are combined. Pareto fronts are computed and examined to demonstrate trade-offs and sensitivities evident in the 6-bus Garver model, showing the applicability of the proposed approach.**

***Index Terms*—load shedding, transmission planning**

I. Introduction

In developing countries, power system planning activities often contend with networks whose design has become sub-optimal due to unplanned load growth, generator aging, or grid extension motivated by political goals. Investment capital is constrained, and load shedding or rotation may already be in effect, raising the debate whether serving more load may be more important than maintaining reserve margins or building additional transmission lines. Optimization of investment is needed to balance competing demands on financial resources, and utilities need to maintain adequate cash flow to expand electricity service for economic growth and poverty reduction.

The transmission expansion problem deals with many factors changing over time, but is often simplified as a static optimization model, minimizing the total investment of network expansion for a single scenario, subject to a number of constraints. [1]. In most of the literature, the static transmission network expansion planning model is typically formulated to minimize investment cost and the load shedding associated with lack of transmission capacity, subject to DC or AC load flow constraints [2], [3].

A probabilistic approach [4] may be better for a small system, because it allows the selection of a given risk level. While there is not an absolute meaning and guidance for metrics such as loss of load probability (LOLP), loss of load frequency (LOLF), and expected energy not-supplied (EENS), past performance is typically used as a relative measure. The application of these indices may be of limited validity if particular outage information is not available, and even historical information may not be relevant to a fast growing system. [5]

This criterion is usually satisfied only in meshed network areas and interconnections of multiple national grids. A relatively large amount of investment would be needed if a small national power system had to ensure the "N-1" security criterion [6], [7], including sub-transmission areas. After the optimization process, a probabilistic approach could be used to evaluate the best sequences considering interruption costs and an hourly load model.

The multi objective consideration of the TEP problem by acknowledging different stake holder constraints has bee presented [8]. It is concluded that although the multi objective approach is much more complex than the single objective one,it gives the decision maker a higher flexibility to operate as well as more information with the solution provided

In this work, a static transmission expansion methodology is presented using a multi-objective optimization framework, where investment cost, operating cost, and load shedding cost are considered in the optimization as three objectives.

The presented work is organized as follows: Section 2 presents the mathematical formulation of the TEP prob-

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lem as a multi-objective problem. Section 3 introduces and then evaluates several scenarios that can each be ingredients of a transmission expansion decision problem, demonstrating results along the way. Section 4 provides a synthesis discussion of accumulated information about likely candidate lines. Finally, conclusions are drawn in Section 5.

The main contributions of this work are:

1) Several Pareto optimal expansion plans are obtained for test system instead of the single transmission expansion plan approach. This process allows a consideration of the tradeoffs between multiple objectives, and reveals some key levels of investment.
2) Variable generation and demand in each bus is considered in the model and comparative analysis with fixed values is carried out to show the impacts on the investment costs, and the sensitivity exhibited by a small power system model.

II. Transmission Expansion Planning Problem Formulation

The AC formulation of the load flow is rarely applied in TNEP literature, since it constitutes a mixed -integer non linear programming (MINLP) problem, which is difficult to solve. For Non-convex MINLP problems, such as the AC-formulated TEP problem, solvers give either a heuristic solution or no solution at all [9]; a globally optimal solution is seldom obtained [10]. Hence, even though the AC network model represents the electric power network accurately, it is preferable to model the TEP problem as a mixed -integer linear programming (MILP) problems via DC approximation of the network [10].

A. Static DC TEP with Load Shedding

The model for the TEP problem pursued in this work is also a static and deterministic modeling i.e.: given a planning horizon with a single stage and scenarios for the generation and power demand, the TEP problem consists in identifying those network branches that should be strengthened, and the number of reinforcements that should be added. The complete TEP model is defined below:

The formulation uses *ij* to represent the branch between bus *i* and *j*. Associated to that branch, C_k, P_k, B_k represent respectively, the cost of the transmission line, power flow, and susceptance. A,is the incidence matrix; g, d and r, are the generation, demand and fictitious generation vectors, respectively. θ is the voltage angle; Ω is the set of candidate branches. Finally, α is the penalization factor of load shedding.

The objective function includes investment, generation, and load-shedding costs. Equality constraints include conservation of power in each node of the system, Kirchhoff's current law(KCL) in the equivalent DC network, Ohm's law and 2nd Kirchhoff's law. The inequality constraints on circuit flow of current and candidate transmission branches is included, as is generation upper and lower bounds. Binary variables x indicate whether a prospective line is built $(x = 1)$ or not $(x = 0)$. The reference bus angle is fixed, while other bus angles are free variables. For a candidate circuit, k in equation if $x_k = 0$, the corresponding flow must be zero, while if $x_k = 1$, equality is enforced as required. A quantity M_k must be greater than the reactance of a candidate line multiplied by any given value of its voltage angle difference [2].

B. Multi Objective Transmission Expansion Planning

A multi objective problem with conflicting objectives has a set of optimal solutions that correspond to trade-offs between objectives. The goal of multi-objective optimization algorithms is to generate these trade-offs. Exploring these trade-offs is important because it provides the system designer/operator with the ability to understand and weigh the different choices available to them.Transmission expansion planning is an inherent multi-objective optimization problem involving perspectives of different stakeholders, such as regulators, investors, network operators and users.

The concept of Pareto optimality (also known as non inferiority or nondominancy) is used to characterized solutions to the multi-objective problem. Qualitatively, a non inferior solution of a multi-objective problem is one where any improvement of one objective function can be achieved only at expense of degrading other.

C. Mathematical Formulation

The investment cost optimization $\min F_1$ can be formulated as

$$\min \mathbf{F_1} \quad = \quad C_k \cdot x_k \tag{1a}$$

The objective of minimizing the total generation cost can be formulated as

$$\min \mathbf{F_2} \quad = \sum_g C_g P_g \tag{2a}$$

The objective of minimizing the total load shed cost can be formulated as

$$\min \mathbf{F_3} \quad = \alpha \sum_i r_i \tag{3a}$$

The factor α is large enough to ensure that all Pareto optimal solutions found by the algorithm have zero curtailment in normal operation. The constraints of the multi-objective optimization problem are mainly those of dc optimal power flow in normal conditions.

III. Scenarios For Garver Model

The technical information of the Garver test system is found in [11]. Initially the generator connected at bus 6 is isolated from the main system. The number candidate branches is 15. In this section, we present a series of insights available from the stated formulation. First, different unit commitment scenarios are studied, to indicate where transmission reinforcement can alleviate sensitive unit commitment scenarios. Second, the sensitivity of the base model to a uniform load growth is considered. Third, the underlying improvements of economic system operation are explored through the congestion cost that has already been avoided by existing lines, and the potential reduction of congestion cost through adding other lines. Fourth, contingencies are studied to determine the minimum investment needed to preserve feasibility for each contingency. The cases have been implemented on a Window Based, 3.2-MHz-based processor with 32GB of RAM using CPLEX 24 under GAMS.

A. Unit Commitment Scenarios

In order to investigate the impact of different unit commitment scenarios on transmission planning, the scenarios in Table I have been evaluated, with a fixed demand of 760 MW to be met. Scenario 1 has generation at bus 1 at the minimum level, generation at bus 6 at the maximum, and generation at bus 3 set to complete meeting the demand of 760MW. In this same logic, the other three generation scenarios are created with a combination of maximum, minimum levels, and one free generator. Table I shows that generation in buses 3 and 6 are important to create feasible regions. In scenarios 3 and 4, min and max levels of generation at bus 1 do not affect the level of load shedding.

TABLE I: Unit Commitment Scenarios

Scenario	Bus 1	Bus 3	Bus 6
1	0	160	600
2	150	10	600
3⋆	0	360	400
4⋆	150	360	250

no load shedding ⋆

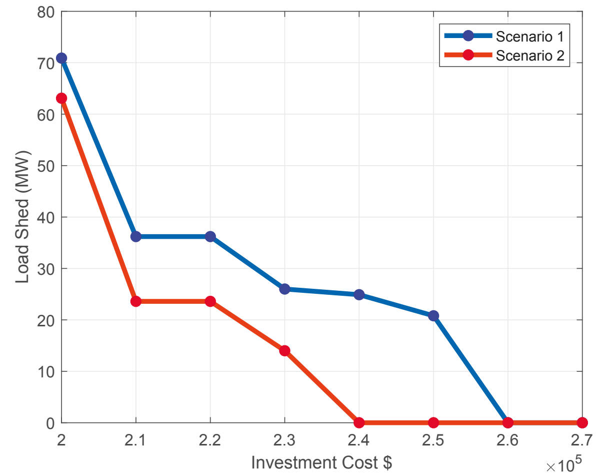

Fig. 1: Pareto front in MW Load Shed versus cap on Investment Cost, %5 Base Demand

B. Expansion Plan for Garver Model with Fixed Demand

The combined Pareto front for Scenario 1 and Scenario 2 is shown in Fig. 1, and the associated circuit additions for Scenario 2 are shown in Table II. The basic TEP solution is also obtained in the Pareto front, which corresponds to an investment of $200 kUSD. Scenario 3 and Scenario 4 were not discussed because there was no load shedding experienced.

Fig. 1 shows that the generation Scenario 2 happens to cause flows for which it is easier to reduce load shedding through investment. At a level of 240,000 USD, no further additions are made. Scenario 1, whose specific investments are detailed in Table II,appears to offer constraints that require more transmission paths to resolve.

In cases where generator location can be chosen, the

TABLE II: Pareto Expansion, Fixed Demand

Inv. Cost (kUSD)	Load Shed (MW)	$n_{2,6}$	$n_{3,5}$	$n_{4,6}$	$n_{3,6}$	$n_{1,3}$	$n_{1,6}$
200	70.9	3	1	3	0	0	0
210	36.2	3	1	2	1	0	0
220	36.2	3	1	2	1	0	0
230	26	3	1	2	1	0	0
240	24.9	3	2	2	1	0	0
250	20.8	3	1	3	0	0	1
260	0	3	1	3	1	0	0

lower investments of Scenario 2 might be obtained. However, the generation scenarios in this small test system are intended to highlight that in a small power system, unit commitment decisions can result in significantly different use of infrastructure. Since it may not be possible to "choose" Scenario 2, it becomes necessary to choose which of load shedding or investment along the lines reported in Table IV are preferable. Examining the candidate lines chosen for high levels of investment shows the converged line choices needed to deal with each generation scenario. In Table: I, we see that due to the unavailability of Gen 3 in unit commitment Scenario 2, that investments are made stemming from Node 3.

C. Expansion Plan for Garver Model with Load Growth

Increasing both generation and load by 5% relative to levels shown Table I allows consideration of the test sytem's suitability under load growth . The obtained Pareto front is shown in Figure 2 and additional circuits added for the worst case generation unit commitment Scenario 1 is shown in Table III. Generally higher levels of load shedding occur, and serving full load through the network requires a higher level of investment following the %5 growth.

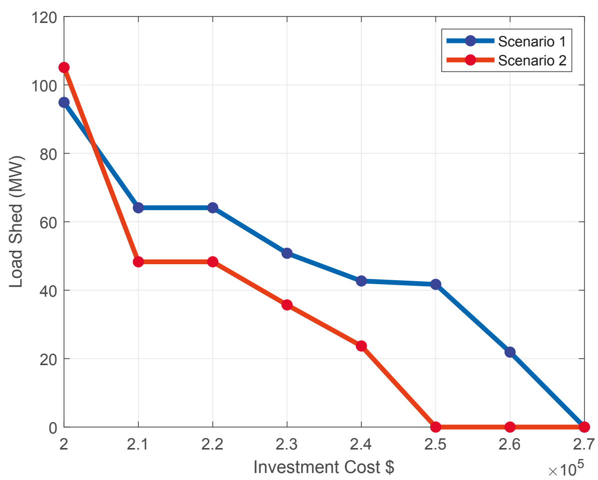

Fig. 2: Pareto front in MW Load Shed versus cap on Investment Cost, %5 Growth in Demand

D. Transmission Congestion and Security

Congestion cost of a line is defined as the opportunity cost of transmitting power through it. Generally congestion cost of line or the opportunity cost of its transmitting power is equal to:

$$C_c = \sum_{ij} P_{ji}(\lambda_i - \lambda j) \quad (4)$$

TABLE III: Pareto Expansion, 5% Demand Growth

Inv. Cost (kUSD)	Load Shed (MW)	$n_{2,6}$	$n_{3,5}$	$n_{4,6}$	$n_{3,6}$	$n_{1,3}$	$n_{1,6}$
200	94.9	3	1	3	0	0	0
210	64.1	3	1	2	1	0	0
220	64.1	3	1	2	1	0	0
230	50.8	3	2	2	1	0	0
240	42.7	3	1	3	1	0	0
250	41.9	3	1	3	0	0	1
260	21.9	3	1	2	1	0	1
270	0	3	2	2	2	0	0

In small power systems, particular corridors may experience congestion and also be a security issue.

Using system parameter data in [11] and the generation table in Table I, the TNEP problem has been solved to determine what minimal investments would yield with feasible flows in spite of a given contingency. The cases are listed in IV. It is interesting to note there is a non-zero congestion cost in the base case (first row). It is clear that generation cost has little variation for a settled case, and that the greatest difference in cost between the cases is F_1, the component related to the cost of investments determined in the TNEP solution, which was allowed to load shed but at a cost. Three other outage scenarios also show a congestion cost, although in a real outage this would be a short-term operation.

TABLE IV: Multi-Objective Cost, Single Contingencies

Case	F_1,inv (kUSD)	F_2,gen (kUSD)	F_3,load (kUSD)	C_c (kUSD)	*Load* MW
Base Case	240	812.9	-	8.91	-
Line 1-2	240	810.3	-	-	-
Line 1-4	250	810.3	-	-	-
Line 1-5	260	812.3	-	8.91	-
Line 2-3	210	823.4	-	7.91	-
Line 2-4	250	810.3	-	-	-
Line 3-5	260	812.9	-	8.91	-

The results in Table IV reflect lines built in response to more significant generation contingencies. Increases in generation cost and load shedding quantities are both more significant. The elevated levels of load shedding and in some cases generation costs that occur in the Garver system are a helpful illustration of the vulnerabilities faced by small power systems.

TABLE V: Multi-Objective Cost, Generation Contingencies

Case	F_1,inv (kUSD)	F_2,gen (kUSD)	F_3,load (kUSD)	C_c (kUSD)	*Load* MW
Gen 2	240	775.3	876	-	10
Gen 3	200	1651	23,652	-	27
Gen 1,2	220	315	14,016	-	160
Gen 2,ln 2-3	320	775	876	-	10
Gen 2,ln 3-5	260	775	876	-	10

TABLE VI: Investment count for Different Contingencies and Scenarios

Contingency	$n_{2,6}$	$n_{3,5}$	$n_{4,6}$	$n_{5,6}$	$n_{2,3}$	$n_{3,6}$
Base Case	2	2	2	0	0	0
Gen 1	3	2	2	0	0	0
Gen 2	3	2	2	0	0	0
Gen 3	0	1	0	0	0	0
Gen 1, 2	4	0	2	2	0	0
Gen 2, Ln 2-3	3	1	2	0	0	2
Ln 1-2	1	1	2	0	1	1
Ln 1-4	2	2	2	0	1	0
Ln 1-5	2	2	2	0	0	0
Ln 2-3	2	2	2	0	0	1
Ln 2-4	2	2	2	0	0	0
5% Growth	2	2	2	0	1	0
Total	26	19	22	2	3	4

IV. Synthesis

The multi objective approach allows to find a set of Pareto optimal solutions where different options trading off a certain level of investment cost and load shedding are to be considered by a decision maker. Table VI shows the most commonly selected lines over the cases studied in this paper, with the most frequently occurring candidates being reported as the first column. From this, a planner weighing the evidence could argue that at least two lines in the corridors represented by the first three columns on the left would be a robust choice.

V. Acknowledgement

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VI. Conclusion

In power systems with a small number of generating units and lines, constrained investment levels, and already insufficient generation, a multi-objective approach to selecting transmission investments is needed. This paper has evaluated the tradeoff of load shedding against investment cost, and has considered the effects of unit commitment pattern changes, line and generator outages, and load growth on line candidate selection. While candidate lines that achieve a meshed system were among the top four selections, the generation/load placement of the Garver system led to optimal investment favouring only some meshing. Exploring a multi-objective approach on the 6 bus Garver system allows an exploration that is grounded in optimal solutions reported in the literature, but reveals new insight into the range and possible conflicts of investment, with quantified tradeoff expressed for investment options. This approach to transmission expansion study can be of use in policy decisions, and a study of concrete options for a real-life national context and transmission company will be evaluated in future work.

References

[1] H. Gil and E. Da Silva, "A reliable approach for solving the transmission network expansion planning problem using genetic algorithms," *Electric Power Systems Research*, vol. 58, no. 1, pp. 45–51, 2001.

[2] L. Bahiense, G. C. Oliveira, M. Pereira, and S. Granville, "A mixed integer disjunctive model for transmission network expansion," *IEEE Transactions on Power Systems*, vol. 16, no. 3, pp. 560–565, Aug 2001.

[3] 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. PAS-93, no. 5, pp. 1390–1400, Sep. 1974.

[4] L. Manso and A. L. Da Silva, "Probabilistic criteria for power system expansion planning," *Electric Power Systems Research*, vol. 69, no. 1, pp. 51–58, 2004.

[5] and J. Choi, , A. A. El-Keib, J. Mitra, , and R. Billinton, "Grid expansion planning considering probabilistic production and congestion costs based on nodal effective load model," in *IEEE PES T D 2010*, April 2010, pp. 1–10.

[6] I. d. J. Silva, M. Rider, R. Romero, A. Garcia, and C. Murari, "Transmission network expansion planning with security constraints," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 152, no. 6, pp. 828–836, 2005.

[7] W. Li and P. Choudhury, "Probabilistic transmission planning," *IEEE power and Energy Magazine*, vol. 5, no. 5, pp. 46–53, 2007.

[8] A. Alarcon-Rodriguez, G. Ault, and S. Galloway, "Multi-objective planning of distributed energy resources: A review of the state-of-the-art," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 5, pp. 1353–1366, 2010.

[9] H. Zhang, G. T. Heydt, V. Vittal, and H. D. Mittelmann, "Transmission expansion planning using an ac model: formulations and possible relaxations," in *2012 IEEE Power and Energy Society General Meeting*. IEEE, 2012, pp. 1–8.

[10] 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, 2012.

[11] L. L. Garver, "Transmission network estimation using linear programming," *IEEE Transactions on Power Apparatus and Systems*, no. 7, pp. 1688–1697, 1970.