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SINGLE OBJECTIVE RISK- BASED TRANSMISSION EXPANSION

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ABSTRACT

This paper proposes a systematic risk based transmission line expansion approach. This expansion method approach comprises of three stages. They are load-driven expansion, security enhancement expansion and risk-based expansion. The main objective of this approach is to minimize the investment cost of the newly added transmission lines by satisfying all the system constraints. In the first stage of transmission expansion the inadequacy problem is identified and it is to be corrected. In the second stage of transmission expansion it is necessary to correct insecurity problem. In the third stage of expansion all the post contingency line overload conditions are eliminated in order to reduce congestion. These three problems are addressed by using Benders decomposition algorithm. The proposed method is illustrated on four-bus and six-bus test system by using MATLAB Software.

***Keywords*: Transmission Expansion, Adequacy, Security, Risk, Benders- Decomposition, Decision making, N-1 criteria.**

1. INTRODUCTION

There is significant evidence that transmission investment in many countries has lagged behind that for load growth and generating capacity additions for some time now [1]. As a result today an increased interest in transmission expansion methods has occurred under deregulation. Adequate transmission capacity is needed to provide security and reliability of the system which are the fundamental needs of modern society. Congestion on a transmission system causes losses and needed extra costs in order to relieve the system from them. Transmission can be a key ingredient in helping to reduce energy prices.

The expansion of the transmission has three purposes: adequacy: to meet future load under normal conditions; security: to meet future load under contingency conditions; risk: to reduce (or eliminate) the need to operate lines at their thermal limits. The third purpose results in relieving congestion in electricity markets that operate based on locational marginal price.

We desire in this paper to develop a transmission expansion method to address all the three purposes. We refer these three as adequacy, security and risk respectively. We know of no systematic approach reported in the open literature addressing these three objectives: adequacy, security and risk. This paper reports on such an approach, which we refer to as risk-based transmission line expansion, which is modular: one may address all three purposes in a systematic fashion or any one of them, or any combination of two of them and here we have eliminate line overloads. An optimization problem is posed to achieve each objective. Each of the three problems utilizes a form Benders decomposition for solution. Benders has been applied to solve power system planning problems before [2][3][4][6] we provide new applications in addressing congestion relief and risk reduction.

2. EXPANSION METHOD

The basic aspects of the expansion method are adequacy, security and risk.

2.1 Adequacy :

The ability of the bulk electric system to supply the aggregate electrical demand and energy requirements of customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system components.

2.2 Security:

The ability of the bulk electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components or switching operations.

In plain language, adequacy implies that sufficient transmission resources are available to meet projected needs plus reserves for contingencies. Security implies that the power system will remain intact even after outages or equipment failures. This is defined as the ability of the system to operate steady-state-wise within the specified limits of safety and supply quality.

2.3 N-1 Criteria:

Generally the security represents the so-called N-1 criteria. “N” is the total number of transmission “elements” in the system and “N-1” is the total system with one element out of service. The ’minus one’ could be a generation unit, a transmission line or a transmission transformer. The basic idea is that even if one component is lost, the system should still satisfy the load requirements without operating violation. This criterion is used to check the security.

2.4 Risk index:

Within the electric network, an individual disturbance resulting in a severe consequence may occur for a number of reasons at any time. The disturbance may result in overload, voltage collapse, or transient instability, drawing the prevailing system to an uncontrollable cascading situation leading to widespread power outages. Here we consider overloads only. Severity assessment provides a quantitative evaluation of what would happen to the power system in the specified condition in terms of severity, impact, consequence, or cost [11][5]. When the line expansion study is performed, the post contingency consequence to be considered is how much the line flow is approaching the limiting capacity. The plan should be developed in such way that post-contingency flow margin is maintained. We define the severity function for overload as.

$$Sev = M \times \varepsilon \qquad (1)$$

Where

ε is the vector measuring how closely the line flow approaches the rating

M is the penalty vector for the specific operating violation.

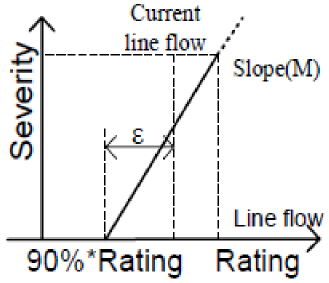

Fig. 1: Overload Severity function

3. FORMULATION AND SOLUTION METHOD

We consider that the three objectives mentioned in the introduction are in fact related problems to be solved together e.g. adequacy expansion has to be done before security expansion):

1. **1.** Adequacy expansion: investment decision and adequacy check;
2. **2.** Security-enhanced expansion: investment decision and security check;
3. **3.** Risk-based expansion: investment decision and risk minimization.

All the above three problems are composed of an economic objective and a reliability sub problem. Four attributes of the overall planning problem drive our choice of solution approach. First, each of the three problems is sequential, where solution to the latter-stage problem (reliability sub problem) depends on determination of the former-stage (economic) objective. For example, in the risk-based expansion, we have to identify the location of the new line before we can evaluate how much risk the system faces. Second, for each of the three problems, the economic objective and the reliability sub problem may be decoupled even though they are related via certain shared variables. Third, the risk evaluation part involves different contingencies, each one effectively a different "scenario" of quantifiable probability. we observe that the investment objectives have integer variables, whereas the reliability sub problems are nonlinear continuous even when using a DC power flow model.

3.1 Benders decomposition

One of the commonly used decomposition techniques in power systems is Benders decomposition. J. F. Benders introduced the Benders decomposition algorithm for solving large-scale mixed-integer programming (MIP) problems. Benders decomposition has been successfully applied to take advantage of underlying problem structures for various optimization problems, such as restructured power systems, operation and planning, electronic packaging and network design, transportation, logistics, manufacturing, military applications, and warfare strategies.

We provide a brief description of the Benders decomposition method, similar to what we have provided in previous publications [11], so that our application to transmission planning is sufficiently self-contained. J.F. Benders introduced the Benders decomposition algorithm for solving large-scale, mixed-integer programming (MIP) problems, which partition the problem into a programming problem (which may be linear or non-linear, and continuous or integer) and a linear programming problem. Problems for which Benders decomposition methods work best are those that have the following structure:

$$\text{Min: } z = \underline{c}(\underline{x}) + \underline{d}(\underline{y}) \qquad (2)$$
$$\text{s.t.} \quad A(\underline{x}) \geq \underline{b} \qquad (2\text{-}1)$$
$$\underline{E}.\,\underline{x} + \underline{F}(\underline{y}) \geq \underline{h} \qquad (2\text{-}2)$$

This problem can be represented as a two-stage decision problem [8]:

Stage 1: Decide on a feasible $\underline{x}^*$ only considering

$$\text{Min: } z = \underline{c}(\underline{x}) + \alpha'(\underline{x}) \qquad (3)$$
$$\text{s.t.} \quad A(\underline{x}) \geq \underline{b} \qquad (3\text{-}1)$$

where $\alpha'(x)$ is a guess of stage 2 regarding stage 1 decision variable x, which will be updated by stage 2.

Stage 2: Decide on a feasible *y** considering (2-2) given *x** from stage 1.

$$\alpha'(\underline{x}^*) = \text{Min: } \underline{d}(\underline{y}) \qquad (4)$$

$$\text{s.t.} \quad \underline{F}(\underline{y}) \ge \underline{h} - \underline{E}.\,\underline{x}^* \qquad (4\text{-}1)$$

Stage 1 is called the master problem, and stage 2 is called the sub problem. Interaction between stages 1 and 2 and how the problem is solved are shown in Fig. 2. The partition theorem for mixed-variables programming problems [7] provides an important optimality rule on which Benders decomposition is based. If we obtain optimal solution (*z**, *x**) in the first stage and then obtain optimal solution *y** in the second stage, if the upper bound *c*(*x**)+*d*(*y**) is equal to the lower bound *z**, then (*z**, *x**, *y**) is the optimal solution for the entire problem. In words, the problem is optimal only when its sub problems are optimal and (2) is satisfied.

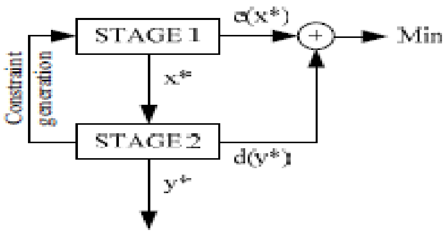

Fig. 2: Solving problem using Benders decomposition

The procedure of Benders decomposition is a learning process (try-fail-try-inaccurate-try-…-solved), and we explain this process as follows. In the left part of Fig. 3, when the stage 1 problem is solved, the optimal value is then sent to stage 2. Stage 2 problem has two steps: 1) Feasibility check sub problem. Check if the optimal solution from stage 1 is feasible. If it is not feasible, the stage 2 problem will send a constraint cut back to stage 1 to let stage 1 remove this infeasible solution set. 2) Optimality check sub problem. Check if the optimal guess of stage 2 from stage 1 is accurate enough. If it is not accurate, a new estimation of $\alpha'(\underline{x})$ is sent to stage 1. If the optimal rule is met, the problem is solved.

3.2 DC flow model and decision variable decomposition

As discussed in [9], a linear (DC) power flow relation is often suitable for representing transmission flows in power system planning problems. The decomposed DC flow model with integer decision variable *x* (1 is build circuit, 0 is not build circuit), which is consistent with formulation [10], is given as follows.

$$f_{ij} - (\gamma_{ij} - \gamma'_{ij}\, x_{ij})'(\theta_i - \theta_j) = 0 \qquad (5)$$

Where

γ	Candidate line susceptance
i / j	Bus index
θ	Bus angle
f ij	Line flow

If candidate circuit is built xij=1 else we taken as 0.

3.3 Problem formulation: adequacy expansion

For this problem, the target is to minimize the investment under the condition all the load is served.

$$\text{Min } \underline{C}\,.\,\underline{x} \qquad (6)$$

$$\text{s.t.} \quad UE = 0 \qquad (6\text{-}1)$$

Where

$\underline{C}$	Cost to build the new line.
$\underline{x}$	Decision variables for the candidate line.
UE	Summation of un served energy.

The sub problem to formulate *UE*, which is feasibility sub problem, also called the minimum load shedding problem (MLS) [13], is as follows.

$$UE = \text{Min } \underline{e}'.\,\underline{r} \qquad (7)$$

$$\text{s. t.} \quad \underline{s}\,\underline{f} + \underline{g} + \underline{r} = \underline{l} \qquad (7\text{-}1)$$

$$f_{ij} - (\gamma_{ij} - \gamma'_{ij}\, x_{ij})'(\theta_i - \theta_j) = 0 \qquad (7\text{-}2)$$

$$|\underline{f}| \le (\underline{f}\,\mathit{max}\ \underline{f}'\ \max .\,\underline{x}) \qquad (7\text{-}3)$$

$$|\underline{g}| \le \underline{g}\ \max \qquad (7\text{-}4)$$

Where

$\underline{r}$	Bus load shedding vector
$\underline{e}$	Bus load shedding penalty vector
$\underline{f}$	Line flow vector
$\underline{s}$	Node-branch incidence matrix
$\underline{g}$	Bus Generation vector
$\underline{l}$	Bus load vector
γij	Existing line susceptance
γij '	Candidate line susceptance
$\underline{f}$ max	Existing line limitation
$\underline{f}$ 'max	Candidate line limitation
$\underline{g}$ max	Generation limitation

3.4 Problem formulation: security-enhanced expansion

After obtaining an adequacy expansion solution, the operating point is feasible under normal conditions. The security-enhanced expansion problem is then performed to ensure that this operating point is feasible under all contingencies. For this problem, the target is to minimize the investment under the condition that all post-contingency line overloads are eliminated.

$$\text{Min } \underline{C}\,.\underline{x} \qquad (8)$$

$$\text{s.t.} \quad MO = 0 \qquad (8\text{-}1)$$

Where

$\underline{C}$	Cost to build the new line
$\underline{x}$	Decision variables for the candidate line
MO	*Summation of overload under all contingencies*

The sub problem to formulate *MO*, which is feasibility check sub problem, called the minimum overload problem, is as follows.

$$MO = \text{Min } \underline{e}'.\,\underline{\eta} \qquad (9)$$

$$\text{s.t.}\quad \underline{s}\ \underline{f} = l - g^{\circ} \qquad (9\text{-}1)$$
$$f_{ij} - (\gamma_{ij} - \gamma'_{ij}\, x_{ij})'(\theta_i - \theta_j) = 0 \qquad (9\text{-}3)$$
$$|\underline{f}| - \underline{\eta} \le (\underline{f}\max + \underline{f}'\max .\underline{x}) \qquad (9\text{-}4)$$

Where

$\underline{g}^{\circ}$ Generation output (fixed/from load-driven problem)

$\underline{\eta}$ Overload vector

The minimum overload problem will always feasible for a connected network.

3.5 Problem formulation: risk-based expansion

The objective of the risk-based expansion problem is

$$Min\ C.x + w\ Pk \textstyle\sum_{k=1}^{N} sev\ k \qquad (10)$$

Where

N Number of contingencies
w parameter for weighting risk relative to cost
k Index of contingencies
Pk Probability of contingency k
Sevk Severity function of contingency *k*

We do not provide the constraints associated with the complete risk-based expansion problem, but they include power flow constraints, operating limits, and security constraints.

As in the security-enhanced expansion problem, the target of the risk-based expansion problem is to minimize the investment under the condition that all post-contingency line overloads are eliminated, i.e.,

$$\text{Min } \underline{C} . \underline{x} \qquad (11)$$
$$\text{s.t. MO} = 0 \qquad (11\text{-}1)$$

where nomenclature is the same as in (8) and (8-1). However, whereas the sub problem of the security-enhanced expansion minimizes composite overload (MO) over all contingencies, here we minimize composite overload risk over all contingencies, which is the optimality sub problem, according to

$$Min\ w\ \textstyle\sum_{k=1}^{N} Pk.sev\ k \qquad (12)$$
$$\text{s.t}\quad \underline{s}\ \underline{f} + g + \underline{r} = \underline{l} \qquad (12\text{-}1)$$
$$f_{ij} - (\gamma_{ij} - \gamma'_{ij}\, x_{ij})'(\theta_i - \theta_j) = 0 \qquad (12\text{-}2)$$
$$|\underline{f}| - \varepsilon \le 0.9\ ((\underline{f}\max\ \underline{f}'\max .\underline{x}) \qquad (12\text{-}3)$$
$$\text{Sevk} = \sum \varepsilon \qquad (12\text{-}4)$$

If the three problems are all to be solved together, then (8), (8-1) are redundant with (11), (11-1), and one of these sets may be eliminated. We include (11), (11-1) so that each of the three problem statements is self-contained. Use of this stage identifies least-cost transmission plans to ensure all post-contingency flows are within their circuit's capacity, use of the latter identifies least cost transmission plans to additionally reduce post contingency loadings near to their capacities, emphasizing contingencies in proportion to their occurrence probability.

3.6 Solution procedure

A flow chart of the solution procedure is given in Fig. 4 and described as follows:

Step 1: Check if the system is adequate; if yes go to Step 3.
Step 2: Perform the adequacy expansion to find a feasible operation point (6).
Step 3: Check if the system is secure, that is, check if the operating point found in Step 2 is feasible under contingency conditions. If yes go to Step 5.
Step 4: Perform the security-enhanced expansion (8).
Step 5: Perform risk evaluation (12).
Step 6: Check if the cost plus risk is the minimum according to Benders rule. If not, return to Step 4.
Step 7: Finish and output results.

The three problems, adequacy expansion, security enhanced expansion, and risk-based expansion, can be solved together, but each may provide useful results in a stand-alone solution. For example, an adequate system may not need the adequacy expansion step and a secured system can directly perform the risk evaluation.

4. ILLUSTRATION

4.1 4-Bus test system

We use a small 4-bus test system from [8], which is shown in Fig. 3. The initial system is inadequate, and so there is to be new generation built at bus 4, necessitating an interconnection and possible system expansion. The generation and load data are in below table I and Table II.

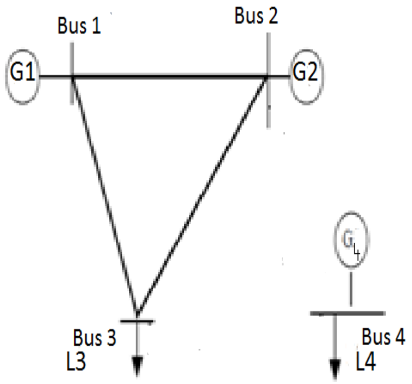

Fig. 3: 4-bus test system

TABLE I
Line Characteristics

Line	From bus	To bus	Susceptance	Capacity	Cost in $
1	1	2	10	200	-
2	1	3	10	200	-
3	2	3	5	200	-
4	2	4	5	150	6,000,000
5	3	4	5	150	5,000,000

TABLE II
Generation Capacity and Loads

Bus	Generation Capacity	Load
1	150	0
2	200	0
3	0	200
4	100	200

4.2 Adequacy expansion

This procedure gives us an adequate system i.e; all the load should be met under normal conditions. The minimum investment needed to make the system adequate is 11,000,000 $. One new line between buses 2 and 4 and one line between buses 3 and 4 are installed. It completed in two iterations. The updated system is shown in Fig 4.

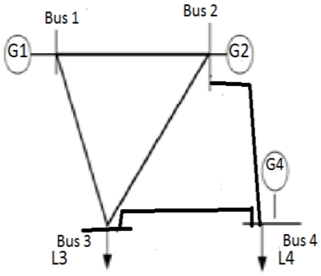

Fig. 4: System after adequacy expansion

4.3 Security enhanced expansion

We need to check if the system is secure or not, i.e., whether all load is met under all considered contingencies, and if not, we need to identify the minimum cost transmission expansion to make the system secure. The N-1 reliability criterion is used here, so that we consider all contingencies comprised of loss of a single component. It takes 2 iterations to converge. In order that in order to obtain a secure system, an additional investment of 12,000,000 $ is needed. Two additional lines are added between buses 2 and 4 .The updated system is as follows in Fig. 5

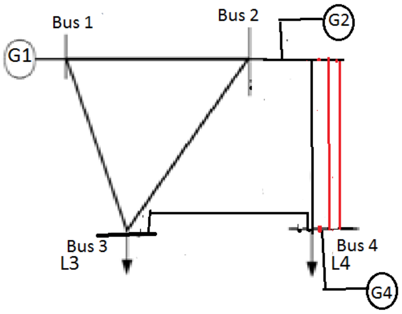

Fig. 5: System after security enhancement expansion

4.4 Risk-based expansion

In this subsection, we use the risk-based expansion to determine additional investment necessary to reduce congestion, i.e., to reduce high post-contingency loadings, emphasizing effects in proportion to the occurrence probability of the contingency which caused them. Contingency probabilities are given in Table III.

TABLE 3
Contingency probabilities

Line	Probability
(1,3)	0.013
(2,3)	0.005
(2,4)	0.015
(3,4)	0.011

It takes 3 iterations to converge and weight *w* is equal to 6000 with a cost of about $11,000,001.56 in order to minimize congestion of the system. It takes another one line between buses 3 and 4.

The Total Minimum investment necessary to make 4-bus adequate, security and to reduce congestion using this approach is $ 3,4000,001.56.

4.5 6 –bus test system

We use a small 6-bus test system from [5], which is shown in Fig. 5. The initial system is inadequate, and so there is to be new generation built at bus 6, necessitating an interconnection and possible system expansion. The generation and load information are shown in Table I, and all line information is in Table II, for both existing and candidate circuits.

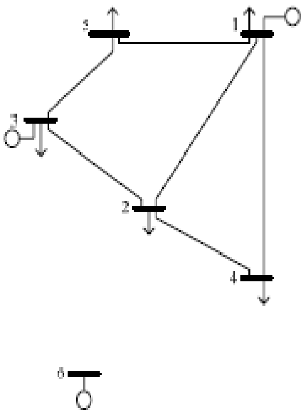

Fig. 6: The 6-bus test system

TABLE 4
Generation Capacity and Loads

Bus	Generation Capacity	Load
1	150	80
2	0	240
3	360	40
4	0	160
5	0	240
6	600	0

4.6 Adequacy Expansion

Here our main objective is to minimise the cost under adequacy condition. The minimum investment needed to make the system adequate is pu$130. An additional two duplicated lines between buses 3 and 5 are installed. One new line between buses 2 and 6 and two lines between buses 4 and 6 are installed. The problem takes 4 iterations to converge. This procedure i.e; adequacy expansion gives us an adequate system, i.e., a system for which all load can be met under normal conditions.

TABLE 5

Line characteristics

Line	Cost(pu$)	Susceptance	Capacity
(1,2)	40	2.50	55
(1,3)	38	2.63	100
(1,4)	60	1.67	30
(1,5)	20	5.00	65
(1,6)	68	1.47	70
(2,3)	20	5.00	110
(2,4)	40	2.50	75
(2,5)	31	3.22	100
(2,6)	30	3.33	100
(3,4)	59	1.69	82
(3,5)	20	5.00	95
(3,6)	48	2.08	100
(4,5)	63	1.59	75
(4,6)	30	3.33	100
(5,6)	61	1.64	78

After adequacy expansion all the load can be met under normal conditions. The updated system is shown in Fig 7.

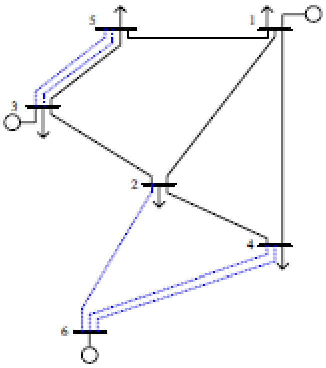

Fig. 7: System after adequacy expansion

4.7 Security enhanced expansion

We need to check if the system is secure or not, i.e., whether all load is met under all considered contingencies, and if not, we need to identify the minimum cost transmission expansion to make the system secure. To obtain a secure system, an additional investment of Pu$50 is needed. Two additional lines are added between buses 2 and 3 and between buses 4 and 6. It takes 6 iterations to converge. The updated system is as follows.

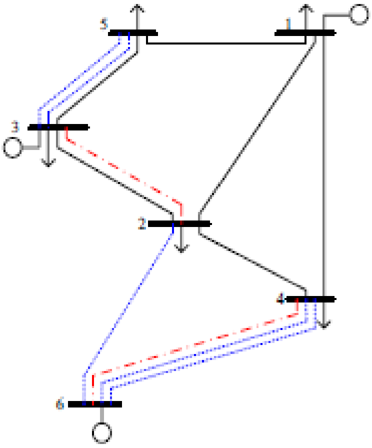

Fig. 8 : System after security enhancement expansion

4.8 Risk-based expansion

In this subsection, we use the risk-based expansion to determine additional investment necessary to reduce congestion. The minimum investment needed to make system to reduce congestion is about pu$ 30.72 at the 2nd iteration. Contingency probabilities are given in Table 6

TABLE 6
Contingency probabilities

Line	Probability
(1,2)	0.011
(1,4)	0.020
(1,5)	0.014
(2,3)	0.005
(2,4)	0.015
(2,6)	0.022
(3,5)	0.015
(3,6)	0.012

The Total Minimum investment necessary to make 6-bus adequate, security and to reduce congestion is pu$ 210.72.

5. CONCLUSION

This Paper presents a single objective risk-based transmission line expansion approach. The approach identifies a least cost transmission expansion plan and it can answer how to expand an inadequate system to adequate one ; how to expand an insecure system to an secure one; and how to manage post contingency risk. Benders Decomposition is used to solve the problem. The results are illustrated on a 4-bus and 6- bus test system using MATLAB Programming.

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