Hybrid AC/DC Transmission Expansion Planning

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***Abstract*—This paper proposes a hybrid algorithm for the ac/dc transmission expansion planning (TEP). The stochastic simulation method would consider random outages of generating units and ac/dc transmission lines as well as load forecast errors. The mixed-integer linear programming problem is decomposed into a master planning problem with integer investment decision variables and subproblems which examine the feasibility of master planning solution and calculate the optimal operation schedule over the planning horizon. The independent system operator would utilize the proposed method to select the optimal set of ac/dc transmission lines for satisfying TEP criteria: supplying load forecasts, minimizing investment costs, and optimizing market operations. The proposed set of dc transmission system may use either current source converters or voltage source converters. Numerical examples illustrate the effectiveness of the proposed TEP model.**

***Index Terms*—DC transmission lines, optimal system operation, reliability, transmission expansion planning.**

NOMENCLATURE

Indices:

b	Index for bus.
e	Index for subperiod.
h	Index for dc converter.
i	Index for unit.
j	Index for ac lines.
k	Index for the dc transmission system.
l	Index for a dc line.
m, n	Starting and ending buses of ac lines.
s	Index of scenario.
t	Index for year.

Parameters:

Bid_{tei}	Bid price of unit i at subperiod e in year t.
CJ	Number of ac candidate lines.
CK	Number of dc candidate transmission systems.
d	Discount rate.
D_{ste}	Load block at subperiod e in year t for scenario s.
DT_{te}	Number of hours at subperiod e in year t.
EJ	Number of existing ac lines.
EK	Number of existing dc transmission systems.
IC_j^C	Investment cost of the candidate ac line j.
$IC_{\mathrm{dc,k}}^C$	Investment cost of the candidate dc transmission system k.
$LOEP$	Loss of energy probability.
LSC_{teb}	Load shedding price of load b at subperiod e in year t.
M	Large positive constant value (e.g., 10e + 8).
NB	Number of buses.
NE	Number of subperiods.
NI	Number of units.
NS	Number of scenarios.
NT	Number of planning years.
x_j	Reactance of ac line j.
$P_{\mathrm{dc},h}^{\mathrm{Min}}, P_{\mathrm{dc},h}^{\mathrm{Max}}$	Minimum and maximum active power transfer of converter h.
$P_i^{\mathrm{Min}}, P_i^{\mathrm{Max}}$	Minimum and maximum generation output of generating unit i.
PL_j^{Max}	Maximum power flow limit of ac line j.
Pr_s	Probability of scenario s.
$\mathbf{A}$	ac bus-unit incidence matrix.
$\mathbf{B}$	ac bus-load incidence matrix.
$\mathbf{C}$	ac bus-converter incidence matrix.
$\mathbf{K}$	ac bus-ac line incidence matrix.

Variables:

LS_{steb}	Load shedding of bus b at subperiod e in year t for scenario s.
$P_{\mathrm{dc,h}}$	Active power withdrawal of converter h.
P_{stei}	Generation dispatch of the unit i at subperiod e in year t for scenario s.
PL_j	Active power flow of ac line j.
$PL_{\mathrm{dc},l}$	Active power flow of dc line l.

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WF, WO	Objective function for reliability check and optimal operation subproblems.
Y_{jt}	Installation status of the candidate ac line j in year t (1 if installed, otherwise 0).
$Y_{\mathrm{dc,kt}}$	Installation status for the candidate dc system k in year t (1 if installed, otherwise 0).
Z_{lower}	Lower bound for TEP objective function.
Z^{upper}	Upper bound for TEP objective function.
θ	ac bus voltage angle.
η, π	Dual variables of equality constraints.
$\mathbf{D}$	Vector of bus loads.
$\mathbf{LS}$	Vector of curtailed loads.
$\mathbf{P}$	Active power output vector of generating units.
$\mathbf{P_{dc}}$	Active power flow vector of dc converters.
$\mathbf{PL}$	Active power flow vector of ac lines.

Others:

$\hat{}$	Given variables.
C	Candidate ac/dc line.
E	Existing ac/dc line.

I. Introduction

HIGH-VOLTAGE direct current (HVDC) transmission technology has salient characteristics in comparison with ac transmission, such as the bulk power delivery through underground or under marine cables, low power losses for long distance transmissions, asynchronous connection of ac systems, and stabilization of ac systems in contingencies [1], [2]. DC transmission is utilized for its power flow controllability which can enhance economic operations, mitigate grid congestion, and prevent cascading outages. DC transmission system is the favorable option for delivering renewable energy from remote sites (e.g., off-shore wind) to load center. Such features have accelerated the deployment of dc transmission in restructured electric power systems.

In contrast to generation expansion planning (GEP) that is mainly driven by market forces, TEP is still regulated and managed by independent system operators (ISOs) in electricity markets. Transmission companies (TRANSCOs) recover their investment from transmission tariffs set by ISOs.

Although there are numerous publications on the optimal expansion planning of ac transmission systems in electricity markets [3]–[16], few studies have investigated the expansion planning of ac/dc transmission systems. References [17] and [18] emphasized that dc transmission systems represent an inevitable TEP alternative in competitive electricity markets. Reference [19] presented two-terminal and multi-terminal dc transmission system (MTDC) planning. MTDC configurations have higher installation costs for providing sophisticated control schemes. These complex control systems will guarantee a reliable operation of dc transmission systems over possible ranges of ac system operations. In order to effectively integrate dc transmission with ac power systems, a comprehensive TEP model would need to be developed for quantifying the benefits of such expansion projects.

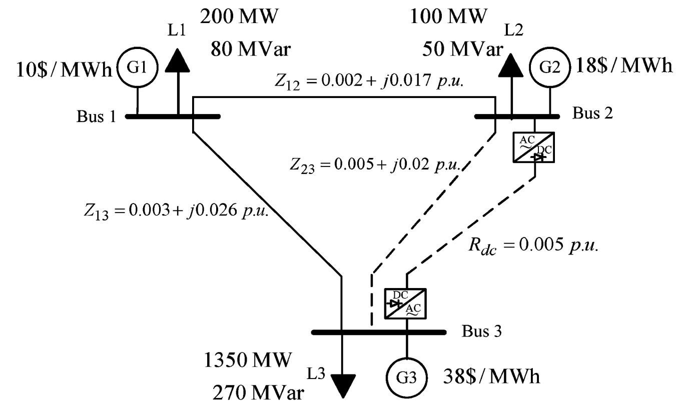

Fig. 1. Three-bus system.

TABLE I
OPERATION WITH AC LINE 2-3 AND DC LINE 2-3 OPTIONS

Items	Capacity	With AC Line 2-3	With DC Line 2-3
G1	300 – 1200 MW	960.69 MW	1184.41 MW
G2	100 – 600 MW	600 MW	500 MW
G3	100 – 300 MW	118.64 MW	0 MW
Line 1-2	500 MW	160.69 MW	384.23 MW
Line 1-3	600 MW	600 MW	600 MW
Line 2-3	900 MW	660.26 MW	781.56 MW
System Operating Cost ($)		$24,915	$20,844

In this paper, we focus on the reliability and the economic assessment of TEP. In order to justify the motivation for ac/dc TEP, a simple case study is considered to examine the economic benefits of controllable dc transmission, which is an important factor in the ac/dc TEP projects. Fig. 1 illustrates a three-bus system with three generating units and two existing ac transmission lines. An additional 300-km ac/dc transmission line extended between buses 2 and 3 will be needed to supply the load of 1,350 MW at bus 3. As such the length of dc line is less than the "break-even distance of 600–800 km" [1], it would be logical to choose an ac line with the investment cost of U.S.$190M instead of a dc line with the investment cost of $320 M. However, Table I shows that if we select the ac line extending from bus 2 to bus 3, cheap generating unit 1 will only be dispatched at 960.69 MW which is less than its capacity of 1200 MW due to the 600 MW limit on line 1-3. The expensive unit 3 is turned on alternatively to supply the 118.64 MW of load. However, if we select the controllable dc line between buses 2-3, the cheap generating unit 1 will be dispatched at its capacity as the dc line allows more power transfer. It is no longer necessary to turn on the expensive generating unit 3 and the total operating cost will be reduced from the U.S.$24 915 (ac option) to U.S.$20 844 (dc option).

For simplicity, we assume that the total load of 1650 MW is averaged hourly throughout the entire year. So, the total annual saving due to the dc transmission selection is about U.S. \$35.66M $((24,915-20,844)\times 8760)$, which means that the dc operation will pay off the difference (i.e., \$320 M − \$190 M = \$130 M) in 4 years (4 × \$35.66 M = \$142.64 M > \$130 M). Therefore, it would be logical based on economics to select the dc transmission over an ac alternative.

This paper discusses a stochastic TEP approach to ac/dc transmission investment while considering transmission reliability constraints. The proposed model would investigate the most economical ac/dc TEP by considering the investment cost of transmission facilities, system operation and load shedding costs, and physical system constraints. It is assumed that the information on GEP and the hourly load forecast is available. Random component outages and load forecast errors are taken into account in the stochastic simulation for the ac/dc TEP. The proposed TEP uses the decomposition optimization approach in which binding constraints are incorporated in the ISO's reliability check and optimal market operation subproblems.

The rest of this paper is organized as follows. Section II models the dc transmission system for a dc power flow analysis. Proposed ISO's TEP and formulations are thoroughly discussed in Section III. Numerical examples are given in Section IV. We summarize our conclusions in Section V.

II. Modeling of DC Transmission System

In general, a dc transmission system consists of two or more converters (rectifiers and inverters), and one or more dc lines that link the converters [20], [21]. Different converter technologies such as CSCs and VSCs are utilized in dc transmission systems. Possible dc transmission system converter configurations include monopolar, bi-pole and tri-pole. However, based on the number of converter stations, the HVDC systems can be classified into back-to-back, two-terminal and multi-terminal connections. In this study, we focus on the monopolar two-terminal and multi-terminal dc configurations for TEP. The proposed mathematical model may be easily expanded to any other dc configurations or operating modes.

The dc transmission system shown in Fig. 2 has two converters linked through a dc transmission. To simplify the dc link model, we assume the total dc terminal withdrawals is zero which means power losses in dc terminals and lines are neglected. Consequently, considering converters 1 and 2 and dc line l in Fig. 2

$$P_{\mathrm{dc},1}+P_{\mathrm{dc},2}=0. \tag{1}$$

For each converter 1 or 2

$$\begin{cases} P_{\mathrm{dc,h}}^{\mathrm{Min}} \le P_{\mathrm{dc,h}} \le P_{\mathrm{dc,h}}^{\mathrm{Max}} & \text{Rectifier} \\ -P_{\mathrm{dc,h}}^{\mathrm{Max}} \le P_{\mathrm{dc,h}} \le -P_{\mathrm{dc,h}}^{\mathrm{Min}} & \text{Inverter} \end{cases}. \tag{2}$$

Here, $P_{\mathrm{dc},h}>0$ indicates a rectifier operation. For the two-terminal dc system, the dc line loading is equal to the converter power. Applying this model to CSC-dc systems, the dc current is unidirectional and the flow direction is changed by reversing the polarity of dc voltage. However, in VSC-dc systems, the dc voltage is unidirectional and the flow direction is changed

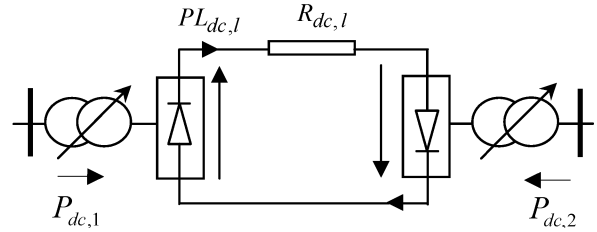

Fig. 2. Monopolar two-terminal dc transmission system.

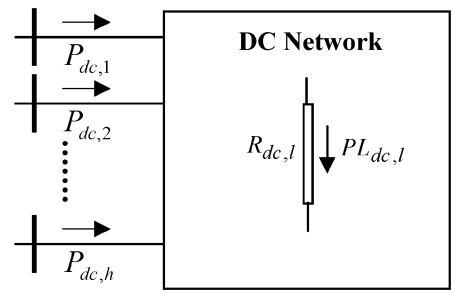

Fig. 3. Multi-terminal dc transmission system.

by reversing the dc current. For CSC-dc systems, the operation at zero power requires a special design which produces high valve losses and harmonic currents. However, in VSC-dc systems, the operation at zero power produces low losses which makes VSC a more favorable option for dc connections up to hundreds mega-watts. For an MTDC system with dc lines l and converters h shown in Fig. 3

$$\sum_{h} P_{\mathrm{dc},h}=0. \tag{3}$$

The set of (2) and (3) would model the dc transmission systems in dc power flow analyses and later will be used in the network reliability check subproblem.

III. AC/DC Transmission Planning Methodology

Fig. 4 shows the proposed ISO's optimal ac/dc TEP algorithm. At first, TRANSCOs submit ac/dc transmission expansion proposals to the ISO. The ISO executes the proposed TEP algorithm to find the least cost investment plans over the TEP time horizon. Every planning year is divided into multiple subperiods. In Fig. 4, Benders reliability cuts will be generated in the case of reliability violations in any subperiods, which are passed along to the master planning problem to change the previous TEP decisions. Once all existing violations are removed, the optimal market operation will be executed to find an upper bound for the TEP problem.

In the optimal operation subproblem, the ISO executes the security-constrained economic dispatch (SCED) with dc lines modeled as constant injections at sending and receiving terminals. If the ISO's TEP stopping criteria cannot be satisfied based on the optimal operation results, Benders optimality cuts will be introduced to change the master planning decisions. This iterative process will continue until a feasible and optimal TEP schedule is obtained. If the ISO's TEP problem cannot converge after several iterations, there would be no feasible TEP schedules

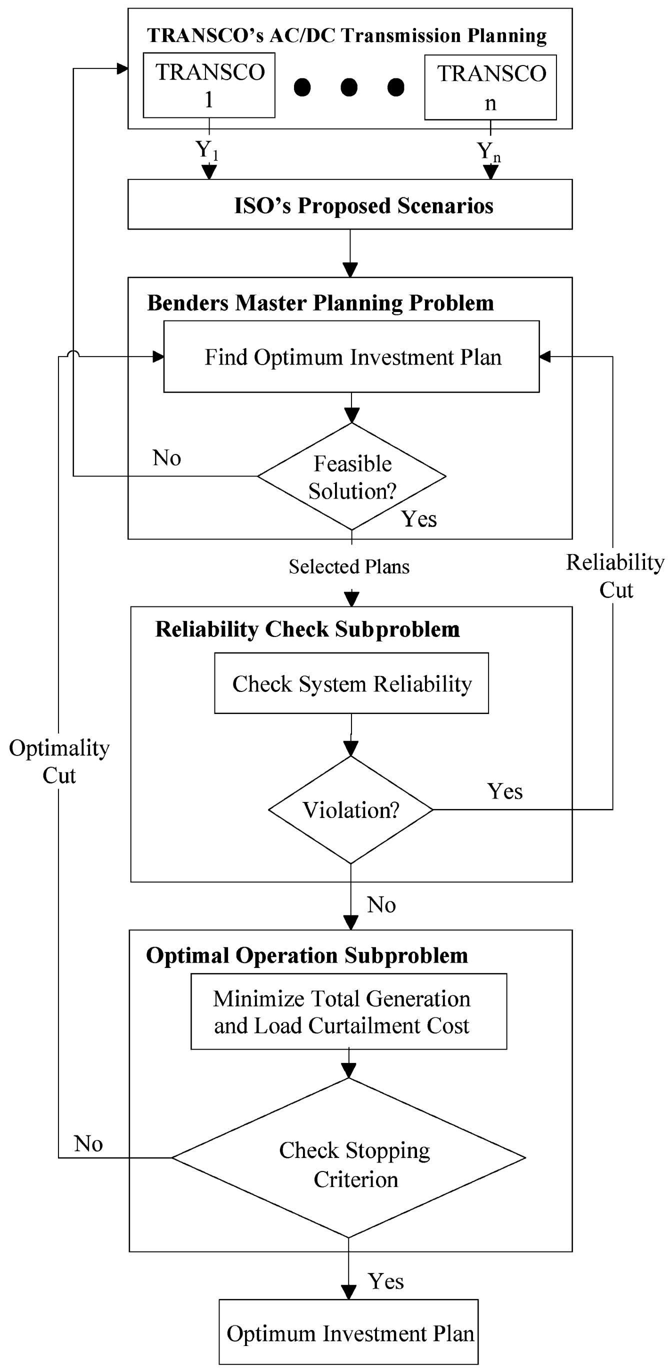

Fig. 4. Flowchart of the proposed hybrid ac/dc TEP model.

based on the given ac/dc transmission candidates. At this time, the ISO may request the participants to revise the candidate list, stop the TEP process, or make other decisions based on market expansion policies. The ISO may also apply load shedding to find a feasible solution based on the loss of energy probability (LOEP) requirement.

In this paper, the scenario analysis for the strategic TEP is implemented using the stochastic simulation method. This simulation is used to examine the ac/dc TEP performance based on random component outages and load forecast errors. The formulations of individual problems/subproblems are discussed as follows.

A. Objective of the ISO in TEP Problem

The ISO's objective in the proposed TEP problem is to minimize the total investment, operation and load shedding costs for the ac/dc transmission systems. The objective function is given in (4) in which all costs are considered as net present values. The first term in (4) expresses the total investment cost for ac/dc TEP proposals. The second term in (4) is the total expected operation cost which is the sum of generation dispatch multiplied by bidding prices for all units. The third term in (4) is the total expected load curtailment cost over the planning time horizon. The approximate maintenance cost over the project life span may be added to (4). The investment and maintenance costs of dc transmission systems depend on the level of reliability requirements [22]

$$\begin{aligned}\text{Min}\quad & \\ Z^{\text{upper}} = & \sum_{t}^{NT}\left(\frac{\sum_{j}^{CJ} IC_j^C * Y_{jt} + \sum_{k}^{CK} IC_{\text{dc},k}^C * Y_{\text{dc},kt}}{(1+d)^{(t-1)}}\right) \\ & + \sum_{s}^{NS}\sum_{t}^{NT}\sum_{e}^{NE}\sum_{i}^{NI}\left(\Pr_s \frac{DT_{te} * P_{stei} * Bid_{tei}}{(1+d)^{(t-1)}}\right) \\ & + \sum_{s}^{NS}\sum_{t}^{NT}\sum_{e}^{NE}\sum_{b}^{NB}\left(\Pr_s \frac{DT_{te} * LS_{steb} * LSC_{teb}}{(1+d)^{(t-1)}}\right). \end{aligned} \tag{4}$$

B. Formulation of Transmission Planning Master Problem

The Benders master planning problem in Fig. 4 is formulated as

$$\text{Min}\quad Z_{\text{lower}} \tag{5}$$

$$s.t.\ Z_{lower} \geq \sum_{t}^{NT}\left(\frac{\sum_{j}^{CJ} IC_j^C * Y_{jt} + \sum_{k}^{CK} IC_{\text{dc},k}^C * Y_{\text{dc},kt}}{(1+d)^{(t-1)}}\right) \tag{6}$$

$$Y_{jt} \leq Y_{j(t+1)} \qquad \forall j, \quad \forall t \tag{7}$$

$$Y_{\text{dc},kt} \leq Y_{\text{dc},k(t+1)} \qquad \forall k, \quad \forall t. \tag{8}$$

The investment cost of ac transmission lines depends on the voltage level, length of the line, line flow capacity, and financial issues such as discount rates. The investment cost of dc transmission systems depends on dc system configuration, number of terminals, rating of each terminal, and converter type (CSC or VSC). Once the ISO obtains the initial transmission planning schedule, the network reliability check subproblem will be used to mitigate ac/dc transmission reliability violations. The network reliability check is formulated next. Once a feasible master planning problem is obtained, the network reliability is examined in the next section.

C. Formulation of Reliability Check Subproblem

In this subproblem, the ISO minimizes the load curtailment at load buses by adjusting generation outputs and dc converter flows. The ISO's reliability check subproblem for the sth scenario at subperiod e in year t is formulated in (9)–(21), shown at the bottom of the page. The ISO checks the network reliability for all scenarios in different years and subperiods. The (10) and (11) represent the transmission planning schedules given by the planning master problem. The set of (12)–(21) represents real power balance at ac buses, each dc system equality constraints, real power flows through existing and candidate ac lines, flow limit of existing and candidate ac lines, flow limit of existing and candidate dc converters, generation limit of each generating unit, and the reference bus angle, respectively. (See the equations at the bottom of the page.)

If the loss of energy probability (LOEP) in (22) is not satisfied in all scenarios and at each subperiod, the Benders reliability cut (23) will be generated and added to the Benders master planning problem presented in (5)–(8)

$$\sum_{s}^{NS}(\mathrm{Pr}_s * WF_{ste}) / \sum_{s}^{NS}(\mathrm{Pr}_s * DT_{te} * D_{ste}) \leq LOEP \tag{22}$$

$$\begin{aligned}&\sum_{s}^{NS}(\mathrm{Pr}_s * WF_{ste}) + \sum_{s}^{NS}\left(\mathrm{Pr}_s \sum_{j}^{NJ} \eta_{stej} * (Y_{jt} - \hat{Y}_{jt})\right) \\ &+ \sum_{s}^{NS}\left(\mathrm{Pr}_s \sum_{k}^{NK} \eta_{stek} * (Y_{\mathrm{dc},kt} - \hat{Y}_{\mathrm{dc},kt})\right) \\ &\leq LOEP * \sum_{s}^{NS}(\mathrm{Pr}_s * DT_{te} * D_{ste}).\end{aligned} \tag{23}$$

Once the network reliability is managed, the ISO examines the optimality of selected schemes as presented in the next section.

D. Formulation of Optimal Operation Subproblem

The objective of the optimal operation subproblem is to minimize the operation and load curtailment costs based on submitted bids and contracts. The ISO's optimal operation for each scenario and each subperiod is formulated as follows:

$$\begin{aligned}\text{Min} \quad WO_{ste} = &\sum_{i}^{NI} \frac{DT_{te} * P_{stei} * Bid_{tei}}{(1+d)^{t-1}} \\ &+ \sum_{b}^{NB} \frac{DT_{te} * LS_{steb} * LSC_{teb}}{(1+d)^{(t-1)}}\end{aligned} \tag{24}$$

$s.t.$

$$Y_{stej} = \hat{Y}_{jt} \quad \pi_{stej} \quad \forall j \tag{25}$$

$$Y_{\mathrm{dc},stek} = \hat{Y}_{\mathrm{dc},kt} \quad \pi_{stek} \quad \forall k. \tag{26}$$

And constraints (12)–(21) are taken into account. Similarly, (25) and (26) represent the transmission planning schedule obtained from the Benders master planning problem. Once the ISO obtains an optimal solution for all scenarios at all subperiods, the ISO calculates the objective function (4) to get Z^{upper}. Then, the stopping criterion (27) will be checked

$$\frac{(Z^{\mathrm{upper}} - Z_{\mathrm{lower}})}{Z_{\mathrm{lower}}} \leq \varepsilon. \tag{27}$$

$$\text{Min} \quad WF_{ste} = \mathbf{1^T} \cdot \mathbf{LS} \tag{9}$$

$s.t.$

$$Y_{stej} = \hat{Y}_{jt} \qquad \eta_{stej} \qquad \forall j \tag{10}$$

$$Y_{\mathrm{dc},stek} = \hat{Y}_{\mathrm{dc},kt} \qquad \eta_{stek} \qquad \forall k \tag{11}$$

$$\mathbf{K \cdot PL_s + C \cdot P_{dc,s} + S_{1,s} - S_{2,s} = A \cdot P_s - B \cdot D_s} \tag{12}$$

$$\sum_h P_{\mathrm{dc},h} = 0 \tag{13}$$

$$PL_{stej}^E = \frac{(\theta_{stem} - \theta_{sten})}{x_j^E} \qquad \forall j \tag{14}$$

$$\left\{\begin{array}{l} PL_{stej}^C - \frac{(\theta_{stem} - \theta_{sten})}{x_j^C} \leq M * (1 - Y_{stej}) \\ PL_{stej}^C - \frac{(\theta_{stem} - \theta_{sten})}{x_j^C} \geq -M * (1 - Y_{stej}) \end{array}\right. \qquad \forall j \tag{15}$$

$$-PL_j^{E,\mathrm{Max}} \leq PL_{stej}^E \leq PL_j^{E,\mathrm{Max}} \quad \forall j \tag{16}$$

$$-PL_j^{C,\mathrm{Max}} \cdot Y_{stej} \leq PL_{stej}^C \leq PL_j^{C,\mathrm{Max}} \cdot Y_{stej} \qquad \forall j \tag{17}$$

$$\left\{\begin{array}{ll} P_{\mathrm{dc},h}^{E,\mathrm{Min}} \leq P_{\mathrm{dc},steh}^E \leq P_{\mathrm{dc},h}^{E,\mathrm{Max}} & \text{Rect.} \\ -P_{\mathrm{dc},h}^{E,\mathrm{Max}} \leq P_{\mathrm{dc},steh}^E \leq -P_{\mathrm{dc},h}^{E,\mathrm{Min}} & \text{Inv.} \end{array}\right. \qquad \forall h \tag{18}$$

$$\left\{\begin{array}{ll} P_{\mathrm{dc},h}^{C,\mathrm{Min}} * Y_{\mathrm{dc},stek} \leq P_{\mathrm{dc},steh}^C \leq P_{\mathrm{dc},h}^{C,\mathrm{Max}} * Y_{\mathrm{dc},stek} & \text{Rect.} \\ -P_{\mathrm{dc},h}^{C,\mathrm{Max}} * Y_{\mathrm{dc},stek} \leq P_{\mathrm{dc},steh}^C \leq -P_{\mathrm{dc},h}^{C,\mathrm{min}} * Y_{\mathrm{dc},stek} & \text{Inv.} \end{array}\right. \qquad \forall h \tag{19}$$

$$P_i^{\mathrm{Min}} \leq P_{stei} \leq P_i^{\mathrm{Max}} \qquad \forall i \tag{20}$$

$$\theta_{ref,ste} = 0 \tag{21}$$

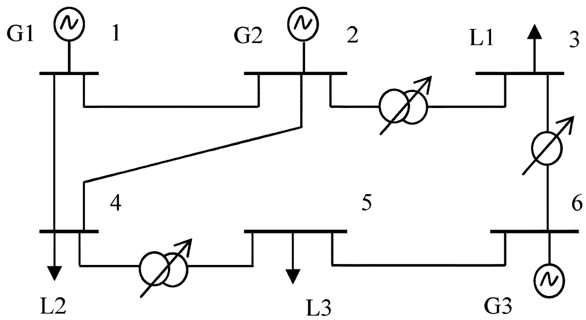

Fig. 5. Six-bus system.

If the stopping criterion (27) is not satisfied, a Benders optimality cut (28) will be added to the Benders master planning problem presented in (5)–(8)

$$\begin{aligned} Z_{\text{lower}} \geq & \sum_{t}^{NT} \left(\frac{\sum_{j}^{CJ} IC_j \times Y_{jt} + \sum_{k}^{CK} IC_{\text{dc},k} \times Y_{\text{dc},kt}}{(1+d)^{(t-1)}} \right) \\ & + \sum_{s}^{NS} (\Pr_s * WO_{ste}) \\ & + \sum_{s}^{NS} \left(\Pr_s \sum_{t}^{NT} \sum_{e}^{NE} \sum_{j}^{NJ} \pi_{stej} (Y_{jt} - \hat{Y}_{jt}) \right) \\ & + \sum_{s}^{NS} \left(\Pr_s \sum_{t}^{NT} \sum_{e}^{NE} \sum_{k}^{NK} \pi_{stek} (Y_{kt} - \hat{Y}_{kt}) \right). \quad (28) \end{aligned}$$

This iterative process will continue until a feasible and optimal ac/dc TEP schedule is obtained.

IV. Case Studies

A six-bus system and the modified IEEE 118-bus system are studied to show the effectiveness of the proposed hybrid ac/dc TEP. The choice of VSC or CSC lines is based on the system performance and economic evaluation. We assume that two-terminal and MTDC transmission systems have similar converter ratings at sending and receiving terminals. The discount rate is 10%. The total permissible load shedding is 1000 MW over the entire planning period. AC/DC line installations are considered at the beginning of each planning year. The stopping criterion ε is 0.05%. All cases are solved using CPLEX 12.0 on a dual core 2.66 GHz CPUs personal computer.

A. Six-Bus System

A six-bus system is shown in Fig. 5. The pertinent data for the transmission network and generating units are listed in Tables II and III, respectively. The bidding strategy of units is assumed to be fixed. Table IV shows the load forecast for the entire planning period of 10 years. Load distribution factors are 0.2, 0.4 and 0.4 for loads at buses 3-5, respectively. There is no generation expansion in this system and the network contains ac transmission at the beginning of planning period.

Tables V and VI show the ac/dc transmission candidates. These candidates are selected based on SCUC results in [23] to link cheap generation stations to high load centers. In this case study, all dc transmission candidates are two-terminal dc systems. We do not consider uncertainties in Case A.

TABLE II
TRANSMISSION LINE DATA

Line No.	From Bus	To Bus	X (pu)	Flow Limit (MW)
1	1	2	0.17	700
2	1	4	0.258	700
3	2	4	0.097	800
4	2	3	0.037	600
5	3	6	0.018	800
6	4	5	0.037	500
7	5	6	0.014	500

TABLE III
GENERATOR DATA

Unit	Bus No.	P_{min} (MW)	P_{max} (MW)	Bid ($/MWh)
G1	1	100	1200	13
G2	2	200	2500	32
G3	6	100	1300	17

TABLE IV
LOAD FORECAST OVER THE 10 YEAR PLANNING PERIOD (MW)

Subperiods	Yr. 1 (MW)	Yr. 2 (MW)	Yr. 3 (MW)	Yr. 4 (MW)	Yr. 5 (MW)
Subperiod 1	1800	1890	1980	2080	2190
Subperiod 2	2560	2690	2820	2960	3110
Subperiod 3	2100	2210	2320	2430	2550
Subperiod 4	2330	2450	2570	2700	2830
Subperiods	**Yr. 6 (MW)**	**Yr. 7 (MW)**	**Yr. 8 (MW)**	**Yr. 9 (MW)**	**Yr. 10 (MW)**
Subperiod 1	2300	2410	2530	2660	2790
Subperiod 2	3270	3430	3600	3780	3970
Subperiod 3	2680	2810	2950	3100	3260
Subperiod 4	2970	3120	3280	3440	3610

TABLE V
CANDIDATE AC TRANSMISSION LINES FOR THE SIX BUS SYSTEM

Line	From Bus	To Bus	X (pu)	Length (Mile)	Flow limit (MW)	Investment Cost (Thousand $/year)
AC1	1	5	0.2	140	700	7900
AC2	2	5	0.15	150	700	8400
AC3	4	6	0.24	160	700	9800

TABLE VI
CANDIDATE DC TRANSMISSION SYSTEMS FOR THE SIX BUS SYSTEM

System	From Bus	To Bus	Length (Mile)	Converters 1 & 2 Capacity (MW)	Investment Cost (Thousand $/year)
DC1	1	5	140	700	11300
DC2	2	5	150	700	12000
DC3	4	6	160	700	11000

TABLE VII
AC/DC TRANSMISSION LINES SCHEDULED TO BE INSTALLED

Candidate	AC1	AC2	AC3	DC1	DC2	DC3
Year	8	1	-	-	-	4

In the summer of the first planning year (subperiod 2 of Yr. 1), the 2560 MW load cannot be served based on the existing transmission network capacity. Consequently, ac/dc transmission candidates listed in Tables V and VI are utilized to find the feasible and most economical TEP. The final ac/dc TEP results listed in Table VII indicate that the candidate lines AC2, AC3, and DC3 are installed in years 8, 1, and 4, respectively, to serve the increasing loads at minimum cost. The proposed solution avoids the potential load shedding and transmission violations over the entire planning horizon.

Based on the TEP optimal solution given in Table VII, the AC2 is selected as the least cost plan in the first planning year. The installation of AC2 would secure the network operation for all subperiods in the planning years 1–3. However, there would still be a line flow violation in the summer of the 4th year (subperiod 2 of Yr. 4). In this year, if we only consider the investment cost of ac/dc transmission candidates, AC3 will be selected for installation as it removes transmission network bottlenecks at the lowest installation cost. However, DC3 is selected instead because its total investment and operational cost savings over the entire planning period are higher than that of candidate AC3. DC3 is a fully controllable dc line that can reduce the congestion in parallel ac lines and decrease the operation cost. Based on TEP schedules in Table VII, the net present values of investment and operation costs over a 10 year planning period are U.S.$101.9M and U.S.$104.2 M, respectively, without requiring any load shedding.

Based on general thoughts [1], [2], dc lines are often recommended over ac lines when dc lines are longer than the break-even length of the line. However, the results of this case study, in which all dc transmission candidates are shorter than break-even-distance, demonstrate the impact of market on TEP analyses. In a market driven TEP, short dc lines could be more attractive than ac lines. Hence, in congested regions and large urban areas, dc transmission systems are often the preferred TEP choice for mitigating congestion, decreasing the operation costs, and reducing consumer payments [24].

B. IEEE 118-Bus System

A modified IEEE 118—bus system presented in Fig. 6 has 54 units, 186 branches, and 91 demand sides. This larger system is selected to evaluate the proposed TEP algorithm. The 118-bus system data is given in http://motor.ece.iit.edu/dc/Planning/IEEE118.xls where 25 ac, 25, dc and 15 MTDC candidates are suggested for a 15-year TEP. Fig. 7 shows the schematic diagram of two-terminal dc transmission candidates (on the left) and MTDC transmission candidates (on the right). Random scenarios are created by the Monte Carlo simulation. The scenario reduction technique [25] is applied to reduce the number of scenarios which are listed in Table VIII. We assumed that load distribution factors at all buses are fixed and all loads have the same annual growth rate of 2%. The total demand through

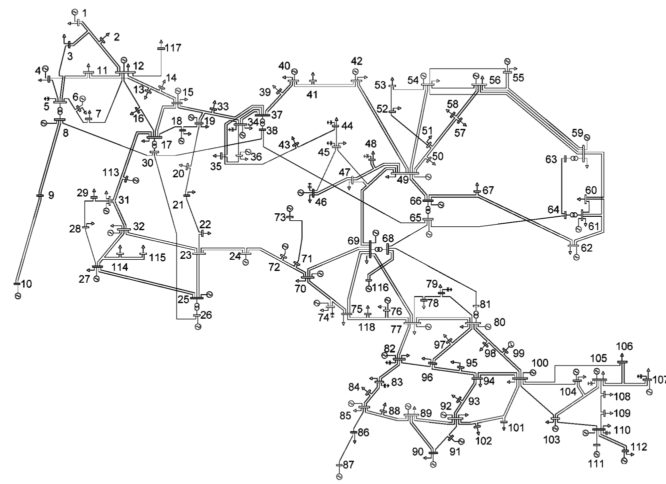

Fig. 6. Modified IEEE 118-bus system.

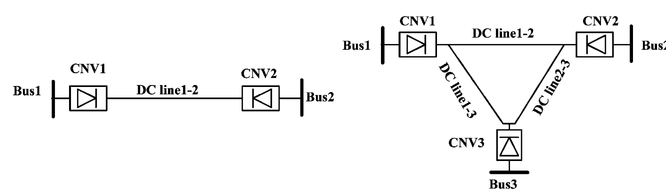

Fig. 7. Two-terminal dc (left) and MTDC (right) candidates.

TABLE VIII
LIST OF OUTAGE SCENARIOS IN THE IEEE 118 BUS SYSTEM

Scenario	Element	Outage Season and Year	Probability
Base Case (S1)	-	-	0.9536
S2	Line 8	Winter, Year 6 & Fall, Year 14	0.0068
S3	Line 37	Spring, Year 10	0.0068
S4	Line 52	Summer, Year 8	0.0068
S5	Line 161	Winter, Year 12	0.0068
S6	Line 150	Fall, Year 11	0.0068
S7	Unit 5	Summer, Year 6	0.0031
S8	Unit 24	Fall, Year 12	0.0031
S9	Unit 29	Winter, Year 13	0.0031
S10	Unit 51	Summer, Year 15	0.0031

first to fourth quarters of the first planning year are 4219 MW, 6000 MW, 4922 MW and 5461 MW, respectively. We use bus LMP differences to select TEP candidates. The additional ac/dc lines would mitigate the line congestion or transfer power from a low-LMP bus, with access to cheap generation, to a high-LMP bus supplied by expansive generating units. The cost of adding a 100 MW ac line is U.S.$1.2M/mile. The cost of adding a 100 MW dc system includes U.S.$20M for two converter terminals (U.S.$10 M per each) and $1 M/mile for the line.

The following two cases are studied

Case 1) TEP without considering any uncertainties

Case 2) TEP with pre-defined scenarios

Case 1: This is the base case power system. The existing system cannot supply the load in years 11–15 without the expansion of existing transmission system. For instance, at year

TABLE IX
SCHEDULED TRANSMISSION LINES IN CASE 1

Line Type	From Bus	To Bus (1)	To Bus (2)	Investment Cost (Thousand $)	Inst. Year
AC	6	113	-	272	13
AC	10	17	-	496	14
AC	15	113	-	258	15
AC	22	46	-	258	15
AC	49	59	-	242	10
DC	7	113	-	1560	15
DC	20	26	-	1747	15
DC	22	46	-	1548	14
DC	60	80	-	2420	13
MTDC	21	32	36	2460	14
MTDC	42	46	54	3073	15

TABLE X
SCHEDULED TRANSMISSION LINE IN CASE 2

Line Type	From Bus	To Bus	Investment Cost (Thousand $)	Inst. Year
AC	5	10	624	15
AC	7	10	496	15
AC	7	113	272	12
AC	10	17	496	15
AC	10	29	258	15
AC	13	17	350	14
AC	15	113	258	15
AC	17	25	688	14
AC	17	33	244	14
AC	18	37	258	14
AC	22	46	258	13
AC	24	26	394	15
AC	25	33	496	15
AC	30	36	258	14
AC	49	59	242	11
AC	59	67	242	15
AC	59	66	320	13
AC	60	80	1304	15
AC	65	69	128	15
DC	10	28	1548	14
DC	25	33	1747	14
DC	49	59	1535	14
DC	59	67	1535	13
DC	59	66	1600	13
DC	60	80	2420	15

15, the load curtailment at bus 59 is 9.35 MW which is due to the congested ac line 59-63. The load curtailment is not allowed at the base case, so the ac line 49-59 is installed in year 10 to minimize the total investment and operation costs during years 10–15 and mitigate the transmission system bottlenecks in year 11. Though candidate lines ac 5-10, dc 5-10, MTDC 5-10-26 and MTDC 5-10-30 can be installed to solve the load shedding at bus 5, the operation and investment costs are minimized when the ac candidate line 6-113 is installed to supply the load at bus 5. Similarly, the dc candidate line 60-80 is installed on this year to transfer the cheap power from unit 36 at bus 80 to a load center at bus 60, remove the congestion, and avoid the load curtailment at bus 59. Table IX shows that 5 ac, 4 dc and 2 MTDC transmission systems are selected out of 25 ac, 25 dc and 15 MTDC candidates. In this case, the net present values of investment and operation costs are \$7.14 M and \$198.43 M, respectively.

Case 2: In this case, most ac/dc transmission installations occur between years 11–15 for supplying the higher demand. When evaluating the transmission reliability for the pre-defined scenarios, the load shedding may be applied to find a feasible solution based on a permissible LOEP. For instance, 23.61 MW of load is curtailed when the scenario S2 (i.e., ac line 8 is on outage at certain subperiods) is considered. Table X shows that 19 ac and 6 dc transmission lines are installed. The net present values are U.S.\$2.49M and U.S.\$205.19M for investment and operation costs, respectively. The difference in total costs between this Case and Case 1 is U.S.\$2.11M which is the cost of maintaining the transmission system reliability.

V. CONCLUSIONS

A hybrid ac/dc TEP model was developed to minimize the total investment, operation, and load shedding costs in restructured power systems. Numerical examples emphasized the fact that an optimal TEP should consider both ac and dc transmission candidates that would guarantee the security and the economics of the reinforced transmission system in the base case and critical contingency situations. The TEP model presented in this paper could include all kinds of dc transmission configurations. Numerical examples show the possibility of additional savings based on the installation of dc transmission systems as compared with ac transmission systems. Such studies rationalize the high cost of installing dc transmission systems or replacing existing ac lines with dc systems in a given right of way. Therefore, the importance of the break-even distance concept should not be over-addressed in TEP studies, since the controllability of dc line flow among other factors are important in the selection of ac/dc transmission systems. In addition, the proposed TEP approach can consider the integration of remotely located, variable and large-scale renewable energy. Considering the unpredictable characteristic of wind energy, the scenario-based simulation representing a range of wind energy forecasts, can be incorporated in the proposed model as we identify a reliable and cost-effective ac/dc TEP strategy.

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