A Comparative Analysis of Transmission System Planning for Overhead and Underground Power Systems using AC and DC Power Flow

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***Abstract*—This paper investigates and compares the results of a transmission system planning approach when both underground and overhead conductors are individually considered. Instead of using a transmission expansion planning of an existing grid, a two-stage transmission planning approach to design a completely new power system is proposed. In addition, the power system is planned by introducing the compulsory N-1 security constraint. Both a relaxed conic AC and a DC power flow models are used and compared. For the purpose of making a comparative analysis of the underground and the overhead transmission system planning, a synthetic test case of the power system of Singapore is used.**

***Index Terms*—Power System Planning, Power Transmission, Mixed Integer Programming, Optimization, DC Power Flow, AC Power Flow, Security Constraints.**

NOMENCLATURE

Sets

Ω_l	Set of lines	
Ω_n	Set of nodes	
Ω_g	Set of generator nodes	
Ω_{fix}	Set of existing lines	

Constants

$\Psi_{i,j}$	Fixed investment cost of lines	$[S\$]$
X_{ij}	Line reactance	$[\Omega]$
G_{ij}	Series conductance of lines	$[S]$
B_{ij}	Series susceptance of lines	$[S]$
B_{ij}^{sh}	Shunt susceptance of lines	$[\mu S]$
P_i^d	Node active power demand	$[MW]$
P_i^{gmax}	Maximum generation of active power	$[MW]$
Q_i^{gmax}	Maximum generation of reactive power	$[MW]$
P_{ij}^{max}	Maximum line active power flow	$[MW]$
Q_{ij}^{max}	Maximum line reactive power flow	$[MW]$
V^{max}	Maximum voltage magnitude	$[kV]$
V^{min}	Minimum voltage magnitude	$[kV]$

Continuous variables

P_{ij}	Active power flow of branch ij	$[MW]$
$Q_{i,j}$	Reactive power flow through lines	$[MVar]$
P_i^g	Active power generated at node i	$[MW]$
Q_i^g	Reactive power generated at node i	$[MVar]$
θ_i	Phase angle at node i	$[rad]$
V_i	Voltage magnitude	$[kV]$

Binary variables

α_{ij}	Decision variable for line ij	

I. INTRODUCTION

The constant emergence and development of modern metropolitan cities introduce a necessity to reconsider how the power system is designed and operated. The very densely populated urban environment represents a big challenge to the traditionally accepted overhead transmission systems. The challenging and excessively expensive land acquisition and common public opposition make the underground transmission lines a safe and reliable alternative with lessened environmental impact.

Recently established metropolis with limited land availability such as Singapore and Hong Kong are pioneering examples of a transition to completely underground power systems, including voltage levels of up to $400kV$. The steady population growth and the continued economic growth set the course for many more metropolis to follow. To account for the inevitable growth in energy demand and determine an optimal grid transition plan, it is important that a power system planning approach is used.

Numerous research efforts in the domain of transmission system planning are reported in the literature. Various methods and applications are studied and proposed. The transmission expansion planning (TEP) is commonly introduced as a single stage deterministic cost optimization method [1]-[3]. Other methods may include stochastic programming or heuristic approaches such as a genetic algorithm or a constructive heuristic algorithm [4]-[6]. In addition, the increase in complexity of the TEP when different applications are considered is tackled by using various multi-stage methods as proposed in [7]-[10].

A market environment with a pool-based market equilibrium for a free trade electricity market is one of the applications considered in the TEP optimization [9]-[11]. The recent rapid technological advancement of distributed generation and electronics introduces load and generation uncertainties that are considered in [4], [12]. The deployment of energy storage systems are combined with a TEP approach by the authors in [13]. Another application described in [3] includes a shunt compensation devices as part of the planning approach. The authors in [14] discuss the importance of short-circuit level constrained TEP. The importance to consider the N-1 security constraint as part of the transmission expansion planning is emphasized in [15], [16].

Due to the complexity of the problem and the difficulty to accurately identify the future demand, a static approach for a single point in time in the future is a most commonly accepted TEP approach [1]-[16]. The TEP problem can be defined using an AC or a DC power flow model. Due to the simplicity and the linearity of the model, a DC power flow is a widely accepted model [13]. However, using the DC model often proves to obtain solutions that are infeasible and problematic in an AC system [1]. Therefore, there is an ongoing effort in exploring multiple linearized and relaxed convex AC models, such as a relaxed second order conic model which is compared to a DC model in [2]. This research interest is highly backed by the recent IT development which introduced new optimization software and a significant rise in computing power.

The research on TEP reported in the literature has in common that only overhead transmission systems are considered and tested [1]-[16]. To the author's knowledge, there is no work investigating and testing an underground transmission system. It is expected that the results of the TEP optimization differ due to the very different electrical characteristics of the underground conductors. Due to the need for high insulation properties, the underground conductors have a significantly higher capacitance and lower reactance and resistance.

This paper investigates how the results of the transmission system planning approach change when underground conductors are considered. Instead of considering an expansion planning of an existing grid, this paper considers a two-stage approach to design a completely new power system for the purpose of comparing an underground to an overhead transmission system planning. In addition, compulsory N-1 security constraint is introduced. Both, a relaxed conic AC and a DC power flow models are used and compared. The comparative analysis is done on a synthetic test case of the power system of Singapore.

II. Transmission System Planning

The objective of the transmission system planning problem is defined as a mixed integer problem as follows

$$\min \quad \sum_{(i,j)\in\Omega_l} \Psi_{ij}\cdot\alpha_{ij} \tag{1}$$

The objective function is a cost function that minimizes the transmission line investment costs with a binary decision variable that obtains the optimal grid configuration. The objective function is subject to constraints (2) - (7) if a DC power flow is considered, and constraints (11) - (20) if a convex AC power flow is considered. The constraints are defined as follows

A. DC Power Flow

$$\sum_{(j,i)\in\Omega_l} P_{ji} - \sum_{(i,j)\in\Omega_l} P_{ij} + P_i^g = P_i^d \qquad \forall i\in\Omega_n \tag{2}$$

$$P_{ij} = \frac{1}{X_{ij}}\cdot(\theta_j-\theta_i) \qquad \forall(i,j)\in\Omega_l \tag{3}$$

$$0\le |P_{ij}| \le P_{ij}^{max}\cdot\alpha_{ij} \qquad \forall(i,j)\in\Omega_l \tag{4}$$

$$0\le |P_i^g| \le P_i^{gmax} \qquad \forall i\in\Omega_g \tag{5}$$

$$-\frac{\pi}{2}\le |\theta_j-\theta_i| \le \frac{\pi}{2} \qquad \forall(i,j)\in\Omega_l \tag{6}$$

$$\theta_{ref}=0 \tag{7}$$

A zero sum of the generated, consumed and transmitted power at each node is introduced with constraint (2), which maintains the power balance of the system. Equation (3) defines a DC power flow calculation. Constraint (4) sets the power flow limits of each branch ij. Each generator node has a maximum generator capacity defined with constraint (5). Equation (6) maintains the grid's operating stability by limiting the phase angle difference. A reference node is chosen and the phase angle at this node is set to zero using constraint (7). Setting a reference node is necessary to bound the phase angle in the optimization problem. It is most common that the biggest generator is chosen as a reference node.

B. AC Conic Power Flow

The nonlinear power flow problem can be reformulated in terms of continuous variables as a convex second-order cone program [17]. The representation of a relaxed conic AC power flow requires the definition of the following variables:

$$\upsilon_i = V_i^2 \qquad \forall i\in\Omega_n \tag{8}$$

$$S_{ij} = V_i\cdot V_j\cdot cos(\theta_i-\theta_j) \qquad \forall(i,j)\in\Omega_l \tag{9}$$

$$T_{ij} = V_i\cdot V_j\cdot sin(\theta_i-\theta_j) \qquad \forall(i,j)\in\Omega_l \tag{10}$$

In terms of the new variables, the constraints are defined as

$$\sum_{(j,i)\in\Omega_l} P_{ji} - \sum_{(i,j)\in\Omega_l} P_{ij} + P_i^g = P_i^d \qquad \forall i\in\Omega_n \tag{11}$$

$$\sum_{(j,i)\in\Omega_l} Q_{ji} - \sum_{(i,j)\in\Omega_l} Q_{ij} + Q_i^g = Q_i^d \qquad \forall i\in\Omega_n \tag{12}$$

$$P_{ij} = G_{ij}\cdot\upsilon_i - G_{ij}\cdot S_{ij} - B_{ij}\cdot T_{ij} \qquad \forall(i,j)\in\Omega_l \tag{13}$$

$$Q_{ij} = -(B_{ij}+\frac{B_{ij}^{sh}}{2})\cdot\upsilon_i + B_{ij}\cdot S_{ij} - G_{ij}\cdot T_{ij} \qquad \forall(i,j)\in\Omega_l \tag{14}$$

$$\upsilon_i\cdot\upsilon_j \ge S_{ij}^2+T_{ij}^2, \quad S_{ij}\ge 0 \qquad \forall(i,j)\in\Omega_l \tag{15}$$

$$\left(V_i^{min}\right)^2 \le \upsilon_i \le (V_i^{max})^2 \qquad \forall i\in\Omega_n \tag{16}$$

$$0\le |P_{ij}| \le P_{ij}^{max}\cdot\alpha_{ij} \qquad \forall(i,j)\in\Omega_l \tag{17}$$

$$0\le |Q_{ij}| \le Q_{ij}^{max}\cdot\alpha_{ij} \qquad \forall(i,j)\in\Omega_l \tag{18}$$

$$0\le |P_i^g| \le P_i^{gmax} \qquad \forall i\in\Omega_g \tag{19}$$

$$0\le |Q_i^g| \le Q_i^{gmax} \qquad \forall i\in\Omega_g \tag{20}$$

Similarly to (2), equations (11) and (12) define the power balance of the system including the reactive power. The AC power flow calculation is obtained through the conic relaxation defined with (15), in combination with the active and reactive line power flow equations (13) and (14). The advantage of the AC power flow calculation to constrain the voltage is defined through (16). Constraints (17) and (18) limit the active and reactive power flow in the lines accordingly, while (19) and (20) define the capacity of the generating units.

Depending on the solver, the second order conic relaxation (15) can have an equivalent representation as follows [18]

$$(2S_{ij})^2 + (2T_{ij})^2 + (\upsilon_i - \upsilon_j)^2 \le (\upsilon_i + \upsilon_j)^2 \quad \forall (i,j) \in \Omega_l \quad (21)$$

When the conic quadratic model obtains a solution, the node voltage magnitudes and angles are recovered using (8) - (10).

If the optimization is considered as a transmission expansion planning, existing lines are fixed by introducing the following constraint

$$\alpha_{ij} = 1 \qquad \forall (i,j) \in \Omega_{fix} \qquad (22)$$

C. N-1 Transmission Expansion Planning

Considering the security requirements for the transmission power systems, the comparative analysis in this paper is done based on N-1 security constraint transmission system planning. This means that contingencies caused by the outage of a transmission line in the grid are considered and avoided by an adequate grid reinforcement. A scenario-based N-1 transmission expansion planning using mixed integer programming is used for this purpose. Both the DC and the AC conic optimizations are redefined as a N-1 transmission expansion planning optimization according to the method detailed in [15].

Since no existing lines are considered when the optimization is initiated, the overall transmission system planning is done in a two-stage process. First, an optimal grid design is obtained by separately using each of the DC and the AC conic transmission system planning optimizations. Then, the grid configuration obtained from each of the optimizations are expanded using a DC or an AC conic N-1 transmission expansion planning respectively.

The DC and the AC conic transmission planning problems are a mixed integer programming and a mixed integer second-order conic quadratic programming optimizations. Both optimization problems can be efficiently solved to optimality by many commercial solvers including CPLEX and MOSEK.

III. Case Study

The comparative analysis of power system planning for the overhead and underground power systems is performed using a case study of a synthetic Singaporean power system. It consists of three voltage levels such as $66kV$ sub-transmission level and $230kV$ and $400kV$ transmission level. The load data is obtained from a realistic synthetic grid generation study of the Singaporean power system, detailed in [19]. The total demand of the system amounts to $7042MW$. Information of the substations and transformer sizing is obtained from reports and documents of the TSO and governmental agencies. The data of the generating units is obtained from reports and data sheets of the Energy Market Authority (EMA) of Singapore. The number of nodes and installed generation capacity per voltage level is given in Table I.

TABLE I
Power System Data

Voltage Level	Number of Nodes	Number of Generator Nodes	Installed Generation Capacity (MW)
$66kV$	130	6	676.1
$230kV$	28	6	7214.5
$400kV$	7	2	5368.9

The set of lines is defined as a set of delaunay triangulation including the second and third delaunay neighbors. The length of the lines is determined as a road distance between the nodes. The electrical parameters of the lines are calculated and used as two different data sets. The line parameters of one set are calculated using an ACSR overhead conductor, and the other set is calculated using a XLPE underground conductor. Three different conductor sizings are selected, one for each of the voltage levels.

In order to be able to validate the comparison of the results between the overhead and the underground power systems, the selection of the conductors is made such that both ACSR and XLPE conductors have an equal current carrying capacity. The parameters of the selected conductors are given in Table II.

TABLE II
Conductor Data

Type	R (Ω/km)	X (Ω/km)	Bsh $(\mu S/km)$	Imax (A)
XLPE 800	0.0284	0.1234	94.20	997
Cardinal 954	0.0728	0.2418	6.990	990
XLPE 1000	0.0226	0.1376	62.80	1131
Bunting 1192	0.0597	0.2375	7.195	1139
XLPE 1200	0.0194	0.1455	56.52	1208
Dipper 1351.5	0.05315	0.2326	7.349	1229

The conductors XLPE 800 and Cardinal 954 are considered for the underground and the overhead $66kV$ voltage level respectively. Similarly, the XLPE 1000 and Bunting 1192 and the XLPE 1200 and the Dipper 1351.5 are used in the $230kV$ and the $400kV$ voltage levels. Since the current carrying capacity of the two conductors in a single voltage level does not exactly match, the minimum of the two values is used as a current limit for both overhead and underground line parameters.

A significant difference in the conductor parameters is noticed when the overhead and the underground conductors given in Table II are compared. The resistance R of an ACSR overhead conductor is in average 2.7 times bigger than a XLPE undergound conductor with an equal current carrying capacity at the same voltage level. Similarly, the reactance X of an ACSR overhead conductor is 1.8 times bigger then a XLPE undergound conductor, while the shunt susceptance is up to 13.5 times smaller than the one from an equivalent XLPE conductor. Such differences in the electrical parameters are the primary reason to investigate and compare the outcome of using power system planning for two different types of power systems.

Even though the conductors and installation costs of an underground power system exceeds the cost of an overhead power system by multiple times, the difference in investment cost of both type of systems is reduced when the challenges of land acquisition in metropolitan areas are considered. This work assumes that the cost of both XLPE and ACSR conductors in a single voltage level is equal. This simplification is done in order to make a valid comparison of the two different type of systems solely based on the difference in the electrical parameters of the grid.

Considering the purpose of this paper to compare overhead and underground power systems using both AC and DC power flows, four different test cases are defined as follows

1) Underground XLPE using DC power flow
2) Overhead ACSR using DC power flow
3) Underground XLPE using AC power flow
4) Overhead ACSR using AC power flow

The results of the test cases are analyzed and elaborated to illustrate the difference in the resultant grid designs when a power system planning optimization is used in the two different types of systems. In addition, it is investigated how the grid design and the grid operation changes when an AC versus a DC power flow model is used as part of the optimization problem.

IV. Results & Analysis

As previously mentioned, the optimization problem is solved in two steps. At the initial step, the power system used as a case study does not have any existing lines and the power system planning is considered as an optimal design of a new grid. This grid configuration is then used as an input for the N-1 expansion planning optimization. Once the optimization is concluded and the N-1 secure grid design is obtained, a MATPOWER power flow analysis is run for each test case.

A. Objective Function

The results of the objective function in the power system planning optimization, that represent the investment cost of the lines, are given in Table III. In addition, the final binary count of the total number of lines for each test case is given in Table IV. For a better understanding of the obtained grid design, the results are shown per voltage level.

TABLE III
Investment Cost of Lines per Case Study

	Investment Cost of Lines			
	66 kV	230 kV	400 kV	Total
XLPE_DC	2.2215E+09	2.0441E+09	2.3786E+09	6.6441E+09
ACSR_DC	2.2483E+09	2.1646E+09	3.4764E+09	7.8893E+09
XLPE_AC	1.7738E+09	1.7658E+09	2.6141E+09	6.1536E+09
ACSR_AC	1.9794E+09	1.9402E+09	2.8556E+09	6.7752E+09

When the overhead power system and the underground power system are compared, it is observed that the cost of the objective of the overhead power system is higher by up to 19% for both AC and DC models. Consequently, when the Table IV is analyzed, the results show that the overhead power system requires more lines to be installed in order to meet the constraints and provide a feasible solution. In addition, if the XLPE underground test case is used to compare the AC and the DC power system planning, it is observed that using an AC power flow model significantly reduces the cost and the total number of lines required for a feasible grid solution.

TABLE IV
Number of Lines per Case Study

	Number of Lines			
	66 kV	230 kV	400 kV	Total
XLPE_DC	210	32	13	255
ACSR_DC	214	35	16	265
XLPE_AC	186	30	14	230
ACSR_AC	199	31	14	244

Even though the investment cost is directly proportional to the total length of the lines, the same does not always apply to the number of lines. In the two test cases where the AC power flow model is used, both the $400kV$ systems have the same number of lines but a different investment cost since different lines are chosen. Having different electrical parameters or different power flow models often results in selecting distinctive lines in each of the grid configurations. The distinctive lines do not overlap when the two power systems are compared. When the overhead and the underground power systems are compared, there are up to 18% or 47 distinctive lines in the grid configurations when the DC model is used. Similarly, there are up to 17% or 42 distinctive lines when the AC model is used. When the AC and the DC power system planning is compared based on the XLPE underground test case, there are up to 23% or 59 distinctive lines in the resultant grid configurations.

B. Power Flow

A power system with significantly different line electrical parameters and line configuration may result with relatively different power flow results. In addition, the solution obtained using a DC power flow can often be infeasible when tested with an AC power flow. To evaluate the power system planning solutions of each test case, a power flow study is done and the results are shown in Table V.

TABLE V
Power Flow Results per Case Study

	Min. Voltage [p.u.]	Losses [MW] / [MVar]	Voltage Angle [deg]	Branch Charging [MVar]
XLPE_DC	0.975	82.4 / 445.4	-14.71	5833
ACSR_DC	0.932	224.6 / 811.4	-33.46	918
XLPE_AC	0.985	76.4 / 407.9	-1.91	6035
ACSR_AC	0.951	208.2 / 767.9	-0.96	782

One of the differences between the underground and the overhead power systems is the voltage drop, which is more notable in the DC power system planning. The overhead ACSR power system has a significantly higher voltage drop of 6.8%, which exceeds the 5% limit and makes the power system infeasible [20]. On the contrary, the underground XLPE power system has a voltage drop of 2.5% which is well within the limits. The smaller voltage drop in the underground system is related to the capacitive effect of the underground conductors which results in a high branch charging as observed in Table V. If the branch charging in the DC underground test case is excluded and set to zero, the voltage becomes 0.928 p.u. and the voltage drop is 7.2%.

When the AC power system planning results are considered, it is observed that the voltage drop is within the proposed limits for both cases. Similarly, the underground power system has a smaller voltage drop due to the capacitive nature of the XLPE conductors.

A noticeable difference is also observed when comparing the power losses. Since the losses are proportional to the resistance R and the reactance X, the ratio between the losses in the overhead and the underground power systems directly corresponds to the difference in the electrical parameters of the both types of conductors. According to Table V, using the AC power system planning provides a better solution when the losses of the system are considered. The smaller amount of losses in the test cases with AC planning compared to DC planning corresponds to different generation profiles and shorter overall line length observed in Table III.

V. Conclusion

A comparative analysis of an overhead and an underground transmission system planning is presented. A two-stage approach to design a completely new power system by considering the N-1 security constraint is proposed. Both, a relaxed conic AC and a DC power flow models are considered and additionally compared. The comparative analysis is done using a synthetic test case of the power system of Singapore.

Results show that optimal planning of an underground power system ideally requires less number of lines and up to 19% lower investment cost. When transmission planning using AC and DC models is compared, the results obtained with the relaxed AC model show a better cost optimal solution and lower number of lines. The results obtained for the two types of power systems show that up to 18% of the lines are unique when the two configurations are compared. Similarly, there are up to 23% distinctive lines when the AC and the DC models are compared.

Due to the significant difference in the line electrical parameters and the line configurations, the obtained solutions show different power flow results when analyzed with MATPOWER. The overhead power system proves to be infeasible when it is planned using the DC model. On the contrary, the underground power system proves to be feasible with voltages well within the limits due to the high capacitance of the lines. However, in addition to the better cost optimal solution, the AC model proves to give a feasible power flow and an improved power flow profile in both type of power systems.

The comparative analysis presented in this paper proves that there can be a significant difference in the transmission planning approach when underground conductors are used. It is of further interest to analyze the results when solely a transmission expansion planning of existing grids is considered. This work can be further extended to include multiple different test cases and investigate if the same conclusions apply.

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