Planning multi-terminal direct current grids based graphs theory

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ABSTRACT
Transmission expansion planning in AC power systems is well known and employs a variety of optimization techniques and methodologies that have been used in recent years. By contrast, the planning of HVDC systems is a new matter for the interconnection of large power systems, and the interconnection of renewable sources in power systems. Although the HVDC systems has evolved, the first implementations were made considering only the needs of transmission of large quantities of power to be connected to the bulk AC power system. However, for the future development of HVDC systems, meshed or not, each AC system must be flexible to allow the expansion of these for future conditions. Hence, a first step for planning HVDC grids is the planning and development of multi-terminal direct current (MTDC) systems which will be later transformed in a meshed system. This paper presented a methodology that use graph theory for planning MTDC grids and for the selection of connection buses of the MTDC to an existing HVAC transmission system. The proposed methodology was applied to the Colombian case, where the obtained results permit to migrate the system from a single HVDC line to a MTDC grid.

Keywords:
Hybrid HVAC-HVDC grids
MST (minimum spanning tree)
MTDC (multi-terminal direct current)
Planning HVDC grids

1. INTRODUCTION
Highly recognized entities in the energy sector has understood the importance of generate social awareness for sustainable development. Such is the case of world energy council (WEC) that in [1] recommends to reduce the use of fossil fuels increasing the use of alternative renewable energy sources, this can be done by identifying different scenarios that facilitate their transition. The previous proposed transition has important challenges in the electrical infrastructure: since by nature, the growth in energy demand is concentrated in regions generally distant from the main and major sources of sustainable renewable generation [2].

This fact creates the need to transmit high volumes of electrical power through very long transmission networks, in most of the cases of several hundred kilometers. As, it is well-known, transmission in HVDC provides a technical solution to this problem [3], taking advantage also of the reduction of environmental impacts due to less right of ways (ROW) utilization. In consequence, the methodologies of transmission expansion planning (TEP) of the current AC systems require to be completed with strategies and methodologies to profit the HVDC developments; such as, HVDC point-to-point line, multi-terminal DC (MTDC) transmission systems, and HVDC meshed network [4, 5].
Originally, the HVDC technology was only used for point-to-point connections, i.e. interconnection of independent AC systems with different operating frequency [6] or systems located at a great distance. However, its evolution is expected to follow a path similar to that of the evolution of HVAC systems. That is, to develop meshed systems that allow the exchange of energy, offering: different power paths between two nodes, increased reliability, availability and quality of the system. Nevertheless, it is to be expected that this process be a long-term vision, given the technological challenges [7] in the development of power breakers in HVDC and communications systems for control systems. Thus, the development of multi-terminal DC systems (MTDC) as an intermediate step of the evolution towards HVDC networks permits to count with the required infrastructure while the HVDC breaker is commercially available. In consequence, the planning of these MTDC networks takes high importance and becomes a preliminary phase to the development of HVDC networks. Figure 1 shows a schematic diagram of connection of a MTDC grid.

![Figure 1. A MTDC grid](image)

Nowadays, there are some projects that use regional MTDC grids in India (Nan’ao island, Zhoushan island, Zhangbei) and United States (atlantic wind connections -AWC- Project, las Tres Amigas superstation project) [8], among others, which show the feasibility of its application using the new HVDC technologies based on voltage source converters (VSC). Some authors have proposed integrated planning of hybrid AC/DC systems based on traditional transmission expansion tools as application of nonlinear programming and differential evolution for the development of MTDC [9], HVDC grids [10] and hybrid AC/DC networks [11]. On the other hand, it is important to develop a planning strategy of MTDC networks that connects the new large renewable generation parks with centers of large energy consumption (demand). At the same time, the planning methodologies shall must consider MTDC as an alternative for interconnection of large AC power systems (i.e. regional or national transmission systems).

This paper proposes of methodology for the planning of MTDC transmission grids for power systems based on voltage source converters (VSC) converter stations. The VSC technology offers better performance compared to line current converters (LCC) [3] and makes feasible the transformation into meshed HVDC networks. Mainly, VSC technology is more flexible to increase the capacity of stations, to control of power flow and disturbances in the system, to select flexibly the control mode [12].

The proposed methodology of MTDC planning considers costs evaluation of HVDC transmission lines based on [13], and the selection of optimal interconnection routes based on graph theory [14]. Other methodologies use mixed-integer linear programming with Benders decomposition [15]. Other studies have applied graph theory for planning in different matters. For instance, [16] used minimum spanning tree (MST) for located Power Flow Controller (PFC) that facilities the control of DC networks. Reference [17] focus in a MTDC planning to locate a topology that minimizes the cost of investment and maximizes the transfer energy from a wind offshore farm to one onshore grid.

Thus, section 2 of this paper presents the research method including the proposed planning methodology (section 2.1), the selection of interconnection nodes to the HVAC system (section 2.2), the selection of the optimal route of the MTDC (section 2.3), the optimal DC voltage selection (section 2.4) based on the cost estimation of converter stations and transmission lines. Then, the proposed methodology is applied for the planning of an MTDC for Colombia that interconnects large sources of wind and solar energy and the connection of the main load centers of the country; as it is shown at section 3. Finally, section 4 presents the conclusions of this paper.
2. RESEARCH METHOD

A MTDC network is defined as an HVDC system with three or more converter stations [18]. Each one of them works as rectifier station (station of generation) or inverter station (station of load). Thus, the MTDC is connected with three or more HVAC buses of an AC system or systems; hence, the system is defined as hybrid HVAC and HVDC the as show in Figure 2.

![Figure 2. Hybrid HVAC and HVDC system](image)

2.1. Planning methodology

Planning a MTDC network requires to know a long-term energy forecast of both power demand and the generation expansion plan based on renewable sources using governmental information as input data, as shown in Figure 3.

![Figure 1. Input information for MTDC planning](image)

The methodology developed for the planning of grids MTDC considers three steps:

- Selection of interconnection AC buses (see section 2.2) based on the “centrality eigenvector” method [19] and [20]. Additionally, include buses in DC for connection of renewable generation (wind and
photovoltaic farms). The voltage of candidate AC nodes is 230kV or higher. This technique has been applied for reactive power planning location [21].

- Selection of optimal MTDC grid route that connects the AC nodes selected in the previous step (see section 2.3). The route is selected as the shortest path based on the graph theory applying the minimum spanning tree (MST) algorithm [14, 22].
- Selection of optimal DC voltage level for the grid defined in step two following the recommendations of International Council of Large Electric Systems given in [23] (see section 2.4).

2.2. Selection of AC interconnection nodes

The MTDC network must be connected to important nodes of the HVAC transmission system. This importance must be based on the voltage level of the node and the number of paths or links connected to these AC nodes. Thus, the candidates AC nodes must be selected in the high voltage; for example 230 kV, 500 kV, or higher. This paper proposes as criteria for the selection of interconnection nodes to apply the “centrality eigenvector” measure defined in the graph theory [20] and followed the recommendations of [19]; and other applications as [22].

The methodology of centrality is selected as part of the study of spectral matrices that identify the property of the graph formed (spectral graph theory) by the admittance matrix of the grid [19], this method “centrality eigenvector” considers the values and vectors of the matrix of the system which give an idea of the importance of a link and its robustness within the system. This criterion can be applied by zones or areas to elect the interconnection node of each AC zone. Hence, the important of a node will be given by its centrality, given by:

$$C_{EV} = \| x_v \| = \left\| \frac{1}{2} \sum_{j=1}^{n} A_Y(v,j) x_j \right\|$$

where $C_{EV}$ is centrality grade of node $v$, $A_Y$ is a complex weighted electrical adjacency matrix obtained from Laplacian $-Y + D(Y)$, where $D$ is the diagonal matrix of incident matrix and matrix $Y$ is the matrix from $Y_{bus}$ system; where $x_j$ is the eigenvector of $A$ for the largest eigenvalue $\lambda$ of $A$. Finally, $j$ represents the total number of nodes under analysis. On the other hand, as AC interconnection nodes, those where large renewable energy sources will be connected are added.

2.3. Selection of optimal route for the MTDC network

At the AC interconnection nodes must be placed at VSC converter station in order to connect the MTDC grid. The next problem is to define the HVDC interconnection route between the VSC stations. Based on graph theory, each VSC station is a vertex in a graph. The connection between nodes or vertices is known as edges. The number edges $V_{(n)}$ for a graph is defined by:

$$V_{(n)} = \frac{n(n-1)}{2}$$

where $n$ is the number of interconnection nodes selected in section 2.2, which can be connected in $(n^{n-2})$ different forms based on the Cayley’s formula [24, 25].

Then, the optimal route for the interconnection of VSC stations must minimize the investment cost of each HVDC line. Each HVDC line is an edge in the graph of alternatives of interconnection. In addition, the investment cost is function of the length of the lines. Thus, this paper proposes to give a weight to each edge based on the distance between the nodes (i.e. the vertices of the graph), which represents the length of the DC lines. Then, the optimal route is computed applying the minimum spanning tree (MST) algorithm that finds the minimal weighted route that joints all vertices of the graph. This optimal route is the MTDC route.

This problem can be modeled by an unaddressed graph $G = (V, E)$ with $V$ defined as the set of nodes (vertex) to be connected, and $E$ the set of possible interconnections between pairs of nodes (edge) [14]. For each edge $(u, v)$ belong to the set possible connections is defined a weight $w(u, v)$ that specifies the cost of the DC transmission line to connect $u$ and $v$ through a subset $T \subseteq E$ (not cyclic) that connects all the vertices of $w(T)$, as follow:

$$w(T) = \sum_{(u,v) \in T} w(u, v)$$

Applying a MST algorithm, the route of minimal cost is found. In order to illustrate to the case of interconnection of VSCs, assume five nodes to be connected. As Figure 4a shown, there are ten possible edges, and for each one a weight is assigned. Figure 4b shows the best option (i.e. the graph with the minimal weight), where the main node is the number one and the total weight of the graph is 3.12 units.
2.4. Selection of optimal voltage of the MTDC network

Once, the set of interconnection nodes between the HVAC network and the MTDC network, and the optimal route are selected the optimal voltage level of the MTDC must be chosen. Then, based on the power that must be transported by the MTDC an optimal basic design is developed following the methodology proposed by CIGRE at [13], and [23]. This methodology has followed in other studies [26].

This methodology takes into account investment cost of lines, Joule and corona losses computation, computation of the ROW as function of voltage level and the section area of the conductor use by pole. Then, for each line of the MTDC the capital expenditure (CAPEX) and the operational expenditures (OPEX) are computed [13]. The OPEX is an annual fixed percentage of the CAPEX, where de cost of the HVDC transmission line in USD per km for overhead lines (OHL) as function of the DC voltage $V$ in kV, the transversal sections of conductor $S$ and the number of conductors by pole $N$ is given by [13]:

$$C_{USD/km} = a + bV + S(cN + d) \quad (5)$$

where $a = 69950$, $b = 115.37$, $c = 1.177$ and $d = 10.25$. These parameters have been obtained by a regression analysis from investment cost of many HVDC lines [13].

The VSC converter station cost ($C_{MME}$) is estimated from [27] as:

$$C_{MME} = 0.083P + 28 \quad (6)$$

where $P$ is the capacity of the VSC converter station in MW. $C_{MME}$ is given in Euros from 2011.
3.2. Selection of AC interconnection nodes and MTDC route

The Colombian transmission system (230 kV and 500 kV) has a model with 106 substations and 300 HVAC lines [28]. The purpose here is to plan a MTDC grid that connects the new center of renewable generation (north of the country) with the main load centers. Thus, the first step is to select the AC nodes where a VSC converter station will be placed to form the hybrid AC/DC network.

The first bus is called “Colectora II” (named here “Bus 1”), where all the wind power plants (WPP) at the extreme north of country will be connected. Then, for each load region the centrality criterion is computed for each node in order to select one AC node for area to be connected to the MTDC. The number of AC nodes in each system are 65 in the Center–East region, 44 in West–Center region, and 34 in the South region; the North zone is not included for the MTDC development. Table 1 presents for each region the first 4 nodes with the higher centrality index based on the proposal of section 2.2.

| Node      | Eigenvector Centrality index | Node      | Eigenvector Centrality index | Node      | Eigenvector Centrality index |
|-----------|------------------------------|-----------|------------------------------|-----------|------------------------------|
| LaTasajera| 0.3814                       | Hidrosogamoso | 0.4318                       | Quimbo    | 0.3728                       |
| Guadalupe IV | 0.2596                    | Barranca | 0.2394                       | Pacifico | 0.2139                       |
| Porce II  | 0.1604                       | CiraInfanta | 0.0771                       | Cartago  | 0.1441                       |
| Antioquia | 0.0780                       | Paipa    | 0.0155                       | Paez     | 0.1273                       |

In consequence, based on Table 1, the selected candidate AC nodes for the development of the MTDC are the first node with the largest centrality index by region. So, the selected interconnection nodes are LaTasajera (“Bus 2”), Hidrosogamoso (called here “Bus 3”), and Quimbo (”Bus 4”). As, section 2.3 states there are 6 links between the four candidate buses, as can see in the Figure 5, and 16 trees based on the Cayley’s formula; i.e. this is the number of alternatives for the development of the MTDC network. Table 2 shows the distance between the selected nodes, the distance between each bus (node) is taken from main road that link these.

| Node          | Colectora II | La Tasajera | Hidrosogamoso | Quimbo |
|---------------|--------------|-------------|---------------|--------|
| Colectora II  | 949          | 949         | 689           | 1346   |
| LaTasajera    | -            | 949         | 689           | 1346   |
| Hidrosogamoso | 689          | 285         | -             | 682    |
| Quimbo        | 1346         | 665         | 682           | -      |

Figure 5. Possible interconnection links between candidate nodes
Applying the methodology describe in section 2.3, with Shortest Path algorithm as part of solution of a Minimum Spanning Tree has the result shown in Figure 6. It can be established that the minimum distance to ensure the link between the generation (substation Colectora II) and the location of all the loads (substations Hidrosogamoso, LaTasajera and Quimbo) is 1639 km.

![Figure 6. Optimal grid for grid MTDC](image)

3.3. VSC size (MW) and MTDC voltage level

As stated at section 0, it is necessary establish the power in MW required for each VSC conversion substation. Table 3 shows the official forecast of the demand to 2040 [29] for each one of the three regions to be interconnected by the proposed MTDC.

| Year | West - Center | Center East | South |
|------|---------------|-------------|-------|
| 2020 | 4331          | 4145        | 2561  |
| 2021 | 4461          | 4299        | 2594  |
| 2034 | 6061          | 6187        | 2929  |
| 2039 | 6655          | 7322        | 3083  |
| 2040 | 6783          | 7636        | 3112  |

On the other hand, the WEC defines three different energy’s growth scenarios [1]. The Tango scenario [30] gives a scenario where the renewable energy plays an important role for generation expansion. In this scenario, 29% of the generation for Latin America and the Caribbean by wind and photovoltaic energy for 2060. At year 2040, it will match to 19% (calculated). In consequence, it is expected that renewable sources supplies 1289 MW of the demand in West Central region, 1451 MW in Center East region and 591 MW at the South Region. In addition, according to the National Expansion Plan 2017 – 2031 [29], a generation of 2912 MW to 3500 MW of wind and solar sources will be expected. Thus, it is reasonable to plan a MTDC network that transport power from WPP projected at the Guajira (connected at Colectora II, or “Bus 1”) to the load demand areas, as Figure 7 shows. Then, following the CIGRE methodology for selecting the DC voltage level [23], a HVDC network at 500 kV gives the best (optimal) costs.

3.4. MTDC CAPEX and OPEX costs

Once defined the technical characteristics of the proposed MTDC, the investment cost (CAPEX) and the operational and maintenance cost (OPEX) are computed based on [13] and [27]. These costs are obtained from minimizing the total cost ($TC$) of the project along the useful life of the project; so:

$$TC = \min \sum \tau (Capex + Opex)$$  (7)
The CAPEX and the OPEX are computed as follow:

- **CAPEX**: the investment cost of VSC converter stations are computed using (4), and indexing money value to 2020 and to US dollars. So, as Table 4 shows a total investment of $ USD MM 1105.81 is required.

**RESULTS: GRID – COLOMBIA -Simulation MATACDC**

![Diagram of Colombia's National Transmission System](image)

Figure 7. Hybrid HVAC and HVDC for Colombian system

| Converter Station | Power Capacity of VSC’s (MW) | Cost MM USD (2020) |
|-------------------|------------------------------|--------------------|
| Colectora II      | 3580                         | 524.41             |
| Hidrosogamoso     | 1451                         | 239.40             |
| Quimbo            | 591                          | 124.28             |
| La Tasajera       | 1289                         | 217.72             |
| **Total**         |                              | **1105.81**        |

Table 4. Power and cost of the VSC converter stations-proposed MTDC

The cost of each section of line HVDC of the proposed MTDC network as shown in Figure 7 is computed by (5). The methodology of CIGRE [13], followed in this paper, optimizes the selection of the conductor, the number of subconductors by pole, such as the investment cost and the losses cost is minimized. Table 5 shows for each line section the selected conductor and the number of subconductors (n) in order to transport the estimated transmission power shown at the table. The costs estimated using (5) are indexed to US dollars of 2020.

| Section Lines of the MTDC | Power MW | Length km | Conductor | Number of Subconductors by pole (n) | USD/km (2020) | MM USD (2020) |
|---------------------------|----------|-----------|-----------|-------------------------------------|---------------|----------------|
| La Tasajera - Quimbo      | 739      | 665       | Tern      | 2                                   | 190.983       | 127.004        |
| Hidrosogamoso - La Tasajera | 2350   | 285       | Rail      | 5                                   | 264.600       | 75.411         |
| Colectora II - Hidrosogamoso | 4164  | 689       | Dipper    | 7                                   | 391.194       | 471.94         |
| **Total**                 |          |           |           |                                     | **726.779**   | **543.515**    |

Table 5. Cost of lines section – MTDC
− OPEX: The annual operation and maintenance costs is computed as 2% of the investment cost of the HVDC lines [13] and 0.5% of the investment cost of VSC converter stations. Thus, the total annual OPEX is $ USD MM 14.96 (Dollars of 2020).

− LOSSES: The losses in converter stations are assumed 1% of the transferred power between DC and AC. The losses at the lines include joule and corona effect, Table 6 shows the total losses for the power transmitted at the MTDC. Taking the average of the energy cost for transmission system in Colombia to January 2020 (cUSD$ 10.044) and assuming a factor loss \( F_{\text{Loss}} \) of 0.44; the estimation of the losses cost \( (\text{Cost}_{\text{Total}}) \) is given by:

\[
C_{\text{Losses}} = \text{Loss}_{\text{Total}} \times 10^3 \times F_{\text{Loss}} \times \text{Cost}_{\text{MW-}h}
\]  

Table 6. Total losses at HVDC line’s sections of the MTDC

| Section Line                  | MW |
|-------------------------------|----|
| La tasajera - Quimbo          | 17.18 |
| Hidrosogamoso – La tasajera   | 19.75 |
| Colectora II - Hidrosogamoso  | 147.44 |
| Total                         | 184.36 |

Finally, the annual cost of losses is estimated $ USD 265544, equivalent to 0.02% of investment cost.

4. CONCLUSIONS

This paper has proposed a methodology of planning the development of a MTDC network based on graph theory. The main contributions are definition of a mathematical criterion for selection of HVAC interconnection nodes based on spectral theory of graphs, known as “centrality eigenvector” method. As, the proposed centrality eigenvector is based on the properties of admittance matrix of the AC network, the proposed criterion takes advantage of the robustness and coupling capacity of transmission HVAC lines measured by the mathematical properties of the Laplacian Matrix. At each selected node a VSC station is placed to connect AC and DC networks. Application of Minimum Spanning Tree concepts from graph theory the MTDC network is used in order to get the minimal path tree; i.e. the MTDC network of minimal distance that joins the VSC converters stations. Applying well-recognized CIGRE methodology, the voltage level of the MTDC is selected. The proposed methodology allows the computation of an estimated investment cost of the MTDC networks, which can be used for planning purposes.

As a test, the methodology was applied to the Colombian case in order to connect a distant large renewable source not-connected to the main AC transmission system to supply power to the main load regions of the country by means of a MTDC. As future work, the proposed methodology can be applied to different countries; as in South America. Then, a second step methodology of planning for regional international MTDC networks must be developed in order to share regional renewable sources.

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