Planning multi-terminal direct current grids based graphs theory

Mario A. Rios, Fredy A. Acero
Department of Electrical Engineering and Electronics, School of Engineering, Universidad de los Andes, Colombia

Article Info

Article history:

Received Apr 14, 2020
Revised Jun 14, 2020
Accepted Jun 28, 2020

Keywords:

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

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.

Corresponding Author:

Mario Alberto Rios,
Department of Electrical Engineering and Electronics,
School of Engineering, Universidad de los Andes,
Carrera 1 No. 18 A – 12, Bogotá, Colombia.
Email: mrios@uniandes.edu.co

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.

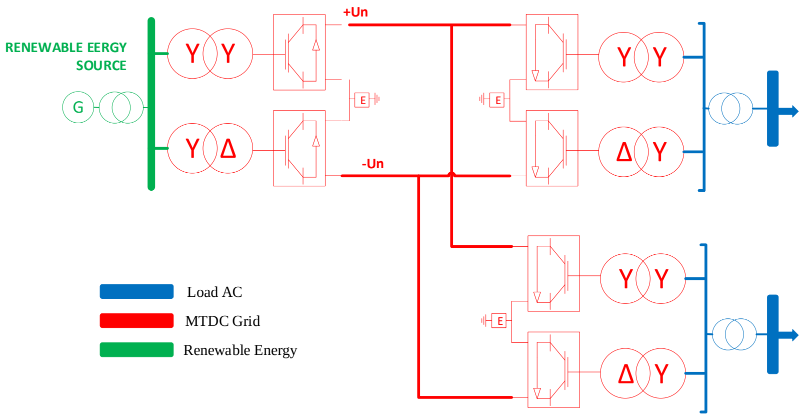


Figure 1. A MTDC grid

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.

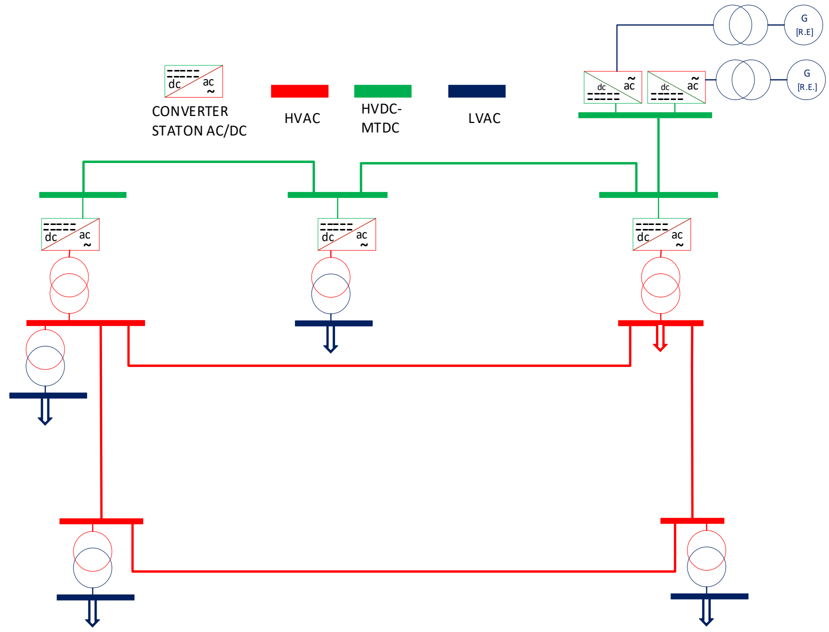


Figure 2. Hybrid HVAC and HVDC system

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.

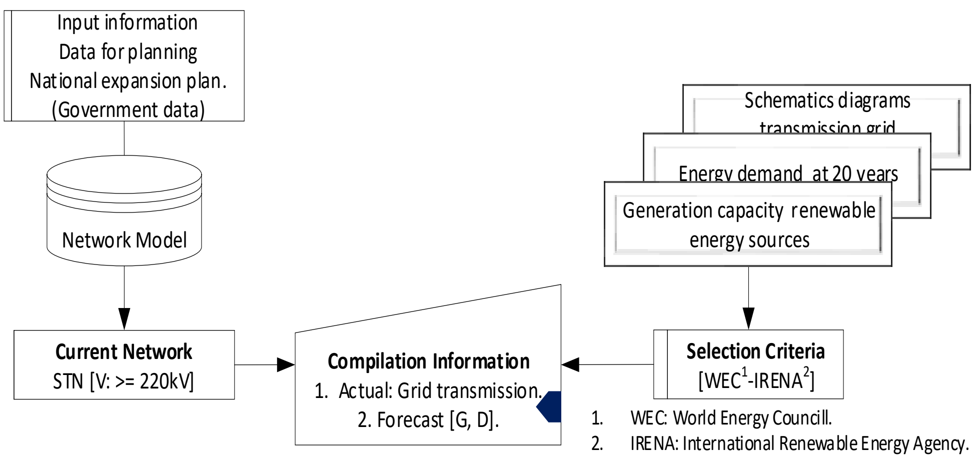


Figure 1. Input information for MTDC planning

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:

$$C_{EV} = \|x_v\| = \left\|\frac{1}{\lambda}\sum_{j=1}^{n}\mathcal{A}_{\Upsilon}(v,j)x_j\right\| \tag{1}$$

where C_{EV} is centrality grade of node v, $\mathcal{A}_{\Upsilon}$ is a complex weighted electrical adjacency matrix obtained from Laplacian $-\Upsilon + \mathrm{D}(\Upsilon)$, where D is the diagonal matrix of incident matrix and matrix Υ is the matrix from Y_{bus} system; where x_j is the eigenvector of A for the largest eigenvalue λ 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:

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

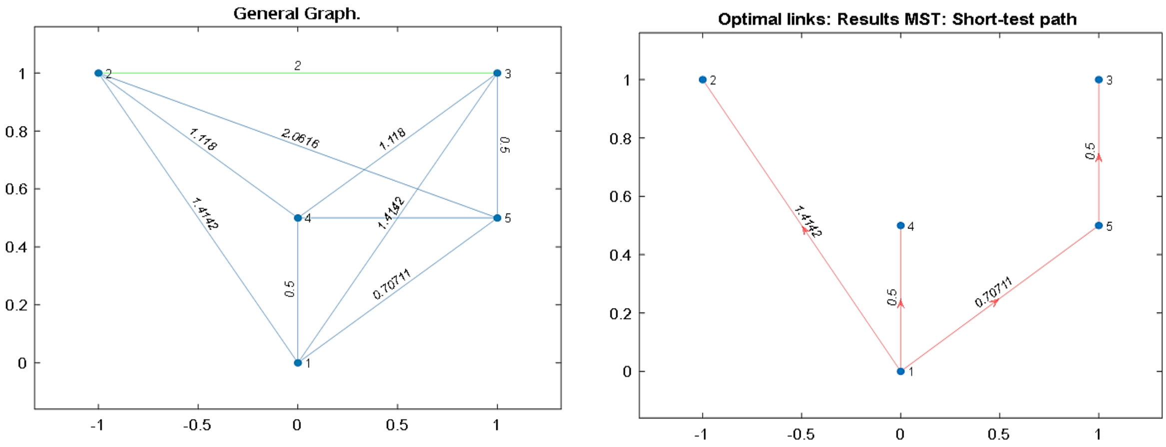
where n is the number of interconnection nodes selected in section 2.2, which can be connected in (n^{n-2}) different forms based on the Cayley's formula [24, 25].

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:

$$w(T) = \sum_{(u,v)\in T} w(u, v) \tag{3}$$

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.



(a) (b)

Figure 4. Optimal route of a MTDC, (a) Graph of alternatives of interconnection and (b) Optimal route obtained by MST

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 ($C_{MM€}$) is estimated from [27] as:

$$C_{MM€} = 0.083P + 28 \quad (6)$$

where P is the capacity of the VSC converter station in MW. $C_{MM€}$ is given in Euros from 2011.

3. RESULTS AND ANALYSIS

3.1. Study case

The proposed methodology has been applied to the Colombian case; taking into account the future generation expansion plan that consists of connection of non-conventional of more than 3274 MW renewable energy sources (Wind farms and photovoltaic farms) for 2027 at the Guajira peninsula at the north of the country. It is also known, that the potential connection of these kind of sources could be around 8557 MW (4127 Eolic and 4430 Solar) in a long term. This region is non-connected to the bulk transmission system. On the other hand, the country has the principal load centers (demand) distributed in three regions: center east, west center and south. The national transmission system has around 15601 km of high voltage AC lines at 230 kV and 500 kV.

In Colombia, the current expansion projects of the network have high delays as consequence of environmental and social constraints that not allow the development of new AC lines. An alternative to solve the difficulties of expansion of the HVAC transmission system (constraints environment, social and capacity of transmission of lines HVAC to large distances) is transfer the bulk of power with grids HVDC, from the new centers of generation renewable the geographical regions where the load is concentrated.

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.

Table 1. Main nodes by centrality criterion – load region

West-Center Region		Center-East Region		South Region	
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	Pacífico	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.

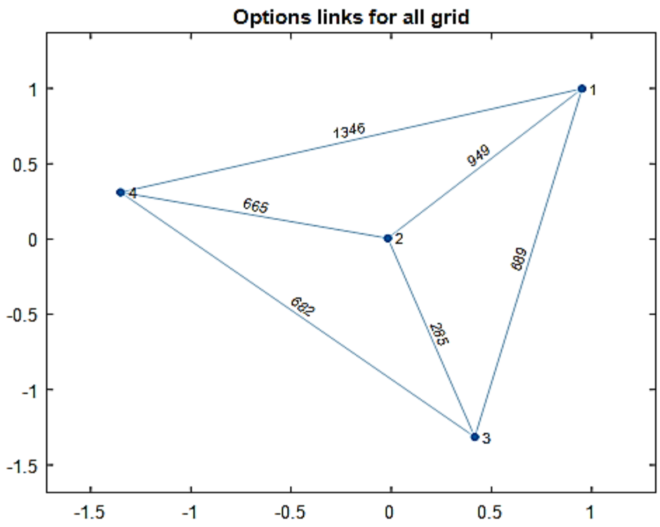


Figure 5. Possible interconnection links between candidate nodes

Table 2. Distance between selected AC nodes – km

Node	Colectora II Bus 1	La Tasajera Bus 2	Hidrosogamoso Bus 3	Quimbo Bus 4
Colectora II (Bus 1)	-	949	689	1346
LaTasajera (Bus 2)	949	-	285	665
Hidrosogamoso (Bus 3)	689	285	-	682
Quimbo (Bus 4)	1346	665	682	-

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.

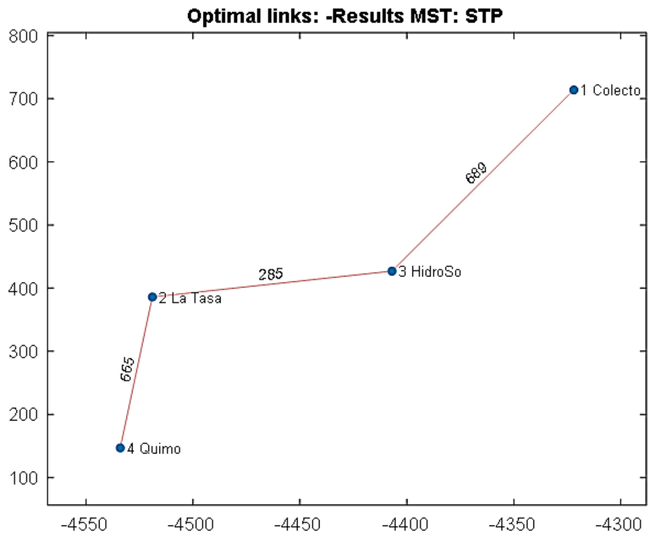


Figure 6. Optimal grid for grid MTDC

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

Table 1. Forecast demand by region MW

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:

$$TC = \min \sum_t (Capex + Opex) \quad (7)$$

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.

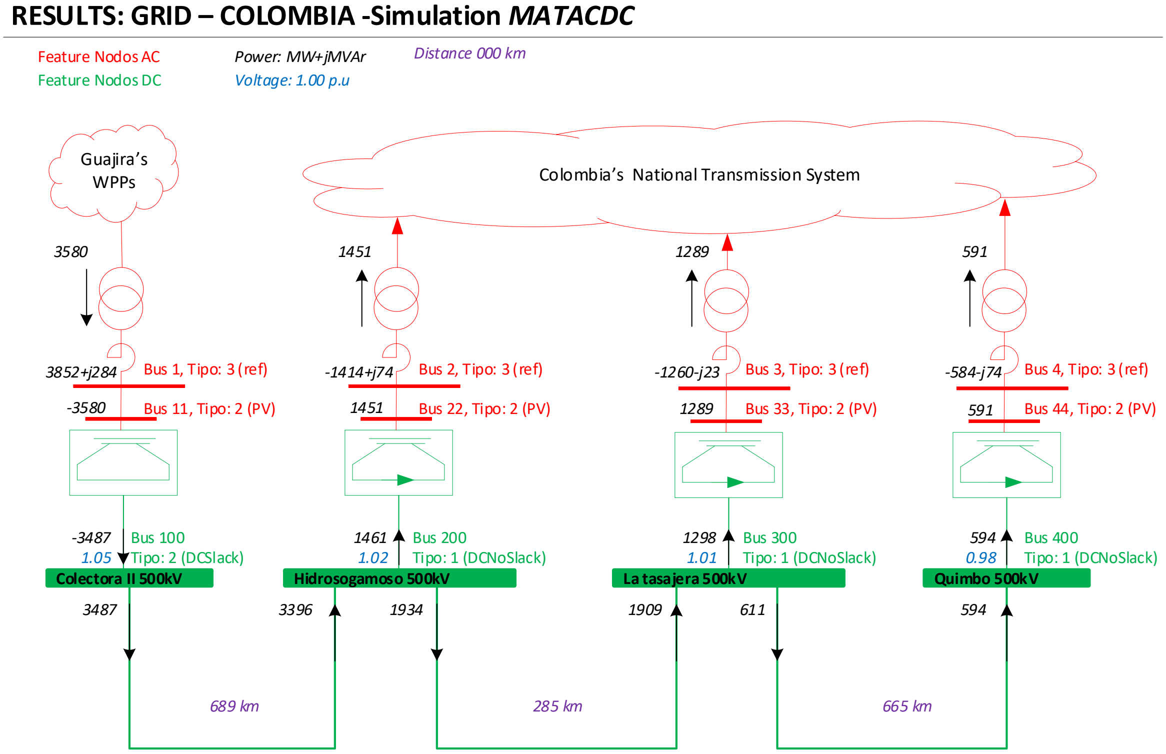


Figure 7. Hybrid HVAC and HVDC for Colombian system

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

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

The cost of each section of line HVDC of the proposed MTDC network as shown in Fgure 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.

Table 5. Cost of lines section – MTDC

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	269.532
Total						471.94

- 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_{Loss} of 0.44; the estimation of the losses cost ($Cost_{kw-h}$) is given by:

$$C_{LOSSES} = Loss_{Total} \times 10^3 \times F_{Loss} \times Cost_{Mw-h} \tag{8}$$

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

REFERENCES

[1] World Energy Council, "World Energy Scenarios 2017, Latin America & The Caribean Energy Scenarios," 2017.
[2] L. Michi, et al., "New HVDC Technology in Pan-European power system planning," *AEIT HVDC International Conference,* pp. 1-6, 2019.
[3] H. Ergun, D. Van Hertem, "Comparison of HVAC and HVDC Technologies," *HVDC Grid: For Offshore and Supergrid of the Future,* pp. 79-94, 2016.
[4] G. Li, C. Li, D. Van Hertem, "HVDC Technology overview," *HVDC grids: for offshore and supergrid of the future,* pp. 45-72, 2016.
[5] J. Sun, M. Li, Z. Zhang, et al., "Renewable Energy Transmission by HVDC Across the Continent: System Challenges and Opportunities," *CSEE Journal of Power and Energy Systems,* vol. 3 no. 4, pp. 353-364, 2017.
[6] M. C. Wrinch, M. A. Tomim and J. Marti, "An Analysis of Sub Sea Electric Power Transmission Techniques from DC to AC 50/60 Hz and Beyond," *OCEANS 2007,* pp. 1-6, 2007.
[7] P. Rodriguez and K. Rouzbehi, "Multi-terminal DC grids: challenges and prospects," *Journal of Modern Power Systems and Clean Energy,* vol. 5, no. 4, pp. 515-523, 2017.
[8] G. Buigues, V. Valverde, A. Etxegarai, P. Eguía, E. Torres, "Present and future multiterminal HVDC systems: current status and forthcoming developments," *International Conference on Renewable Energies and Power Quality (ICREPQ'17),* vol. 1, no. 15, pp. 83-88, 2017.
[9] R. A. de Araujo, J. Pissoloto, C. A. Castro, S. P. C. Torres, "Integrated AC/DC transmission expansion planning model considering VSC-MTDC systems," *IEEE Power & Energy Society General Meeting,* pp. 1-5, 2017.

[10] M. P. Gonzalez, and M. A. Rios, "Comparison of HVDC-Grid and HVAC into Transmission Expansion Planning," *IEEE Andescon*, 2018.
[11] A. H. Dominguez, L. H. Macedo, A. H. Escobar, and R. Romero, "Multistage Security-Constrained HVAC/HVDC Transmission Expansion Planning with a Reduced Search Space," *IEEE Transactions on Power Systems,* vol. 32, no. 6, pp. 4805-4817, 2017.
[12] M. A. Elizondo et al., "Interarea Oscillation Damping Control Using High-Voltage DC Transmission: A Survey," *IEEE Transactions on Power Systems,* vol. 33, no. 6, pp. 6915-6923, 2018.
[13] Join Working Group B2/B4/C1.17, "Impacts of HVDC Lines on the Economics of HVDC Projects," *CIGRE,* 2009.
[14] T. H. Cormen, C.H. Leisserson, R. L. Rivest, C. Stein, "Introduction to Algorithms," *MIT Press. 2nd Ed. London. McGraw-Hill,* 2001.
[15] M. Moradi-Sepahvand, T. Amraee, "Hybrid AC/DC Transmission Expansion Planning considering HVAC to HVDC Conversion under Renewable Penetration," *IEEE Transactions on Power Systems, in-press,* 2020.
[16] H. Xie, Z. Bie and G. Li, "Reliability-Oriented Networking Planning for Meshed VSC-HVDC Grids," *IEEE Transactions on Power Systems,* vol. 34, no. 2, pp. 1342-1351, 2019.
[17] M. Nazari, "Control and planning of Multi-Terminal HVDC transmission Systems," Doctoral Thesis in Electrical Engineering, KTH Vetenskap Och Konst, Stockholm, Sweden, 2017.
[18] O. E. Oni, A. G. Swanson, R. P. Carpanen, "Impact of LCC-HVDC multiterminal on generator rotor angle stability," *International Journal of Electrical and Computer Engineering (IJECE),* vol. 10, no. 1, pp. 22-34, 2020.
[19] A Torres, G. J. Anders. "Strategic Lines and Substation in an Electrical Power Networks," *Innovations in Power Systems Reliability,* pp. 169-189, 2011.
[20] W. Zhifang, A. Scaglione, R. J. Thomas, "Electrical Centrality Measures for Electric power Grid Vulnerability Analysis," *49th IEEE Conference on Decision and Control,* pp. 5792-5797, 2010.
[21] D. Bharti, M. De, "A Centrality Index Based Approach for Selection of Optimal Location of Static Reactive Power Compensator," *Electric Power Components and Systems,* vol. 46, no. 8, pp. 886-899, 2018.
[22] M. M. H. Elroby, et al., "Generalized optimal placement of PMUs considering generalized system observability, communication infrastructure, and quality of service requirements," *International Journal of Electrical and Computer Engineering (IJECE),* vol. 10, no. 3, pp. 2824-2841, 2020.
[23] Join Working Group B2/B4/C1.17, "Recommended Voltages for HVDC Grids," *CIGRE,* 2017.
[24] R. Diestel, "Graph Theory," *Electronic Edition 2000, Springer Verlag, New York,* 2000.
[25] M. Aigner, and G. M. Zeigler, "Proofs from THE BOOK," *4th Ed., Electronic Edition 2000, Springer Science & Business Media,* 2010.
[26] D. Paez, and M. A. Rios, "Cost Analysis of an MTDC for interconnection Guajira-Cerromatoso-Panama," *FISE-IEEE/Cigre Conference,* 2019.
[27] A. L'abbate, "Draft deliverable d3.3.2. Review of cost of transmission of infrastructures, including crossborder connections," *Realise Grid,* pp. 16-19, 2011.
[28] A. Ayo, and M. A. Rios, "Alternatives of Development of SINEA Project in VSC-HVDC," *IEEE Transmission and Distribution Conference and Exposition,* 2020.
[29] UPME, "Reference Generation and Transmission Expansion Plan 2017 – 2031, (In Spanish)," *UPME, Mining and Energy Minister,* 2018.
[30] A. Vera, and M. A. Rios, "Planning a Latin America SuperGrid: a First Approach," *ANDESCON,* 2018.

BIOGRAPHIES OF AUTHORS

Mario Alberto Ríos: received a degree in electrical engineering in 1991 and a M.Sc. Degree in electrical engineering in 1992, both from Universidad de los Andes, Bogotá, Colombia. He received a Ph.D. degree in electrical engineering from INPG-LEG, Grenoble, France, in 1998, and a Doctoral degree in engineering from Universidad de los Andes, in 1998. He worked as a consultant engineer in ConCol (now WSP), Bogotá, Colombia, during 12 years. Also, he was a Research Associate at the University of Manchester (formerly, UMIST). Currently, he is Full Professor at the Department of Electrical Engineering, School of Engineering, Universidad de los Andes, Bogotá, and director of the Power and Energy Research Group of this university

Fredy Armando Acero Niño: Electrical engineer from Universidad Nacional de Colombia 2004, with certified posgraduate studies in transmission and distribution of electrical systems from Universidad de los Andes 2016 at Bogotá, Colombia. Nowadays, carry out Master Thesis in Electrical Engineering, Universidad de los Andes, Bogotá, 2020. Work as Leader in Engineering of Control and Protections at Grupo de Energía de Bogota (GEB), Colombia. e-mail: fa.acero10@uniandes.edu.co