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Power Flow Solution on Multi-Terminal HVDC Systems: Supergrid Case

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Abstract. *High Voltage Direct Current* (HVDC) systems offer distinct advantages for the integration of offshore wind farms to inland grid system. HVDC transmission system based on *Voltage Source Converter* (VSC) enables multi-terminal use HVDC for the integration of large-scale wind power in the North Sea. That network requires a special formulation for power flow analysis as opposed to the conventional method employed on AC networks. This paper presents a sequential AC/DC power flow algorithm, which is proposed for the analysis of *multi-terminal VSC HVDC* (VSC-MTDC) systems. This sequential power flow method can be implemented easily in an existing AC power flow package and is very flexible when compared with unified methods. *Gauss-Siedel* is used to solve DC power balance equations, as it offers two keys advantages: very fast and simple computational implementation, and errors do not accumulate during the calculation. The algorithm is tested using the WSCC 3-machine, 9-bus system with a 3-terminal MTDC network and the results are compared with those obtained from DIgSILENT® PowerFactory™ demonstrating the validity of the proposed algorithm. As an aggregate value, a representative test case of the projected scheme for the phase I of the Supergrid project on the North Sea is presented. The proposed approach presented in this paper is used to calculate DC power flows for some scenarios.

Key words

HVDC transmission, HVDC converter, load flow analysis, VSC HVDC.

1. Introduction

There are some challenges for the power systems in coming future. One of them is meeting the rising energy requirements in a manner that is: *sustainable, secure, and competitive*. No single answer is readily available but there are several aspects to consider regarding primary resources [1]: (i) greater energy efficiency and conservation, (ii) increased use of resources that are secure, indigenous, sustainable, *clean* and competitive. A realistic solution is based on a primary energy source that is secure, clean and fuel cost-free: *wind power.* Europe's offshore wind potential is enormous and able to meet Europe's demand seven times over. There are 150 GW of offshore wind projects already in various stages of planning [2]. A 126 GW capacity is expected to be installed in 2030, producing 530 TWh of electricity annually.

The North Sea has a vast potential for renewable energy generation: offshore wind power, tidal and wave energy. *High Voltage Direct Current* (HVDC) systems are more flexible than their AC counterparts. This offers distinct advantages for integrating offshore wind farms to inland grid system. The *Voltage Source Converter* (VSC) HVDC transmission system enables fast and flexible control active and reactive power, and can alleviate the propagation of voltage and frequency deviations due to wind variations ascertain to wind strength. It seems that advances on technologies open the door for VSC HVDC systems at higher voltage and at higher power range, which is making *multi-terminal HVDC* (MTDC) system a technical possibility [3], [4], [5], [6], [7].

A meshed MTDC system enables the opportunity to construct a whole overlaying DC *Supergrid*, a truly pan-European electricity super highway [8]. Supergrid is defined as "*a pan-European transmission network facilitating the integration of large-scale renewable energy and the balancing and transportation of electricity, with the aim of improving the European market*" [9]. The future vision of an offshore SuperGrid can be outlined as: (i) Transcends weather systems and national, boundaries, reducing generation variability, (ii) Perform the dual role of connecting wind farms and acting as an interconnector, (iii) Facilitates European Trading, (iv) Less overhead costs (£/MW) than some on-shore shallow connections.

These projects and ideas have received widespread attention from both politicians and the press. However, within the technical community, a lot of scepticism exists [10]. VSC-HVDC appears to be a technical solution for Supergrid transmission system, DC side behaves as current source, rendering power flow reversal a trivial task [11], [12]. The operating principles of VSC are completely different from those of current source converter (CSC). For this reason, the power flow algorithm developed for CSC-MTDC cannot be directly used for the VSC-MTDC.

The solution methods for HVDC power flow are generally divided in *sequential* and *unified methods*. The unified (simultaneous) method was originally suggested by Arrillaga [13]and co-workers.The AC and DC system are solved together [14], [15], the DC equations along with the power flow equations, consequently solving the combined set simultaneously. The sequential method was proposed by Reeve et al [16]. It solves the DC system equations using interface variables as computed from AC power flow [17], [18]. Sequential approach is quite easy to develop and be integrated into an existing AC based power flow software while for the unified approach a whole implementation is needed. Few publications have been lately for MTDC.

Temesgen et al [19], presents a numerical iteration based upon Newton-Raphson approximation for lossless converter stations using the unified approach. *Beerten et al* [20], [21] have used the sequential approach for the MTDC power flow problem. They have included converter losses and have defined the power set-points with respect to the system bus. In [22] the concept of distributed DC voltage control for power flow is included.

This paper presents a general method for VSC-MTDC power flow calculations based on the Gauss-Seidel approach. The proposed method is used for the DC network and does not impose any restrictions on the topology configuration (more than two terminals) or on the configuration of the DC network.

The proposed approach is implemented on an existing AC power flow package and it is tested over a test network. Section II shows the algorithm for MTDC network power flow analysis. Section III presents simulation and results over WSCC 3-machine, 9-bus system [23] with a 3-terminal MTDC network using a proposed approach implemented in MATLAB and integrated into the AC power flow program. The results obtained with the presented approach are compared with those obtained using DIgSILENT PowerFactory v14.0.525.1 [24]. This has demonstrated the validity of the proposed algorithm. Section IV presents a test case based on a representative/realistic scheme for the phase I of the Supergrid project on the North Sea. The proposed approach presented in this paper is used to calculate DC power flows during several scenarios. Finally, the conclusions of this work are discussed.

2. MTDC Network Power Flow Analysis Problem

A classical problem of circuit theory is to find all branch currents and all node voltages of an assigned circuit. In general, the power flow problem pertains in finding the zero of a set of nonlinear equations starting from an adequate initial guess. The most general form of the power flow equations is a set of *differential-algebraic-equations* (DAE) in steady-state [25]. The most common formulation of the power flow equations is reduced to the algebraic representation (1):

$$\mathbf{g}(\mathbf{x}) = \mathbf{0} \tag{1}$$

where **g** is the set of algebraic equations that define the power balance at network buses. The classical formulation of AC power flow equations for a n node network, defines the nodal injected current vector ($\mathbf{I}=[I_1, I_2, I_n]^T$) as function of the voltage vector ($\mathbf{V}=[V_1, V_2, V_n]^T$) and the admittance matrix ($\mathbf{Y}=\{Y_{ij}\}$)

$$\mathbf{I} = \mathbf{YV} \tag{2}$$

$$I_i = \sum_{j=1}^{n} Y_{i,j} V_j \qquad i = 1, 2, ..., n\text{-}1 \tag{3}$$

which leads in writing the complex power injections (**S**) at nodes:

$$\mathbf{S} = \mathbf{VI}^* = \mathbf{VY}^*\mathbf{V}^* \tag{4}$$

In the classical power flow formulation, the variables are voltage amplitudes and phases at load nodes, reactive powers (Q_i) and voltage phases at generator PV nodes and active (P_i) and reactive power at the slack node.

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{5}$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{6}$$

A complete explanation for the classical AC power flow can be found on [26], [27], [25], [28].

In the case of a n_{dc} DC nodes networks, each node is characterized by nodal voltage ($U_{dc,i}$), and nodal ($P_{dc,i}$) power injected into the DC network. The current injected at the i-th DC node ($I_{dc,i}$) can be written as:

$$I_{dc,i} = \sum_{\substack{j=1 \\ j\neq i}}^{n_{dc}} Y_{dci,j}\left(U_{dc,i} - U_{dc,j}\right) \qquad i = 1, 2, ..., n_{dc}\text{-}1 \tag{7}$$

Combining the current equations into a matrix form:

$$\mathbf{I_{dc}} = \mathbf{Y_{dc}U_{dc}} \tag{8}$$

where the DC current vector $\mathbf{I_{dc}}=[I_{dc,1}, I_{dc,2}, ..., I_{dc,ndc}]$, $\mathbf{V_{dc}}=[U_{dc,1}, U_{dc,2}, ..., U_{dc,ndc}]$ is the DC voltage vector and $\mathbf{Y_{DC}}=\{Y_{dci,j}\}$ is the DC bus admittance matrix. The current injections $\mathbf{I_{dc}}$ are not known prior to the power flow solution for the DC network.

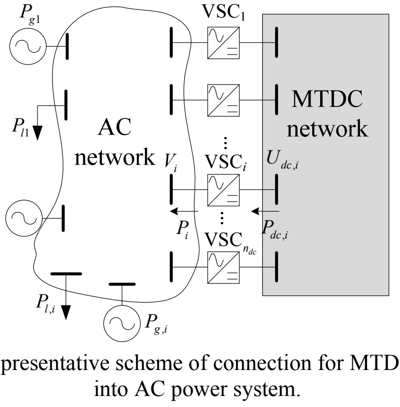


Fig. 1. Representative scheme of connection for MTDC system into AC power system.

DC network as well as the AC network each has to be solved iteratively in the sequential approach. In order to include the VSC-HVDC stations into the AC power flow equations, some considerations from power flow point-of-view should be taken into account. Two reactive power controls functions are included into VSC-HVDC stations from the AC network side: (i) *Q-mode*, where the reactive power injected (Q_i) into the AC network is kept constant and (ii) *V-mode*: the reactive power converter injection (Q_i) is enough to keep the AC node voltage magnitude (V_i) constant. On the DC network side, there are two different control functions for each converter: (i) *P-control*: The active power (P_i) injected in the AC network is kept constant and can be modelled as a constant negative load (PQ-node). (ii) U_{dc}*-control*: The converter controls its active power injection (P_i) to keep its DC node voltage constant (U_i). Therefore it is modelled as a voltage controlled source (PV-node).

All except one converter work on *P-control*, controlling the active power injection into the AC network; one converter controller must work as U_{dc}-control and it is named *DC-slack converter*. The actual value of the active power injection of this converter is not known prior the power flow solution. For the AC power flow, the DC slack converter is the node that covers the DC network losses.

For a bipolar DC network, the active power injected at the *i*-th node can be written as:

$$P_{dc,i} = 2U_{dc,i} I_{dc,i} \tag{9}$$

Assuming a lossless converter station: $P_i = P_{dc,i}$, then the voltage at this node ($U_{dc,i}$)can be calculated from:

$$P_{dc,i} = 2U_{dc,i} \sum_{\substack{j=1 \\ j \neq i}}^{n_{dc}} Y_{dci,j} \left(U_{dc,i} - U_{dc,j} \right) \tag{10}$$

It is evident, from (10), nonlinear nature in terms of voltage node ($U_{dc,i}$) of this problem. Numerical methods are employed to obtain a solution that is within an acceptable tolerance. A suitable method to solve (10) is the *Gauss–Seidel (GS) method*, also known as the *Liebmann method*, under this approach. The GS algorithm is applied on the power flow equations of the DC network. The following steps describe this procedure:

Step 0: Formulate and assemble $n_{dc} \times n_{dc}$ DC admittance matrix $\mathbf{Y_{DC}}$.

Step 1: Assign initial guesses to (n_{dc}-1) unknown node voltage:

$$U_{dc,i}^{(k+1)} = 1.00 \text{ p.u}, \qquad i = 1, 2, 3, \ldots (n_{dc}-1) \tag{11}$$

The DC slack node is assumed as n_{dc}th node.

Step 2a: For the *P-control* VSC converter node, find $U_{dc,i}$

$$U_{dc,i}^{(k+1)} = \frac{1}{Y_{dci,i}} \left[\frac{0.5 P_{dc,i}}{U_{dc,i}^{(k)}} - \sum_{\substack{j=1 \\ j \neq i}}^{n_{dc}} Y_{dci,j} U_{dc,j}^{(k)} \right] \tag{12}$$

where *k*=iteration number.

Step 2b: For faster convergence, apply acceleration factor (α) to *P-Control* VSC converter node:

$$U_{dc,i,ACEL}^{(k+1)} = U_{dc,i,ACEL}^{(k)} + \alpha \left(U_{dc,i}^{(k)} - U_{dc,i,ACEL}^{(k)} \right)$$

where subscript *ACEL* defines the accelerated value.

Step 3: Check convergence. That is, the value of the difference of the node voltage between successive iterations should be less than a tolerance value ε.

Step 4: Find DC slack node power:

$$P_{dc,i} = 2U_{dc,n_{dc}} \sum_{j=1}^{n_{dc}-1} Y_{dci,j} \left(U_{dc,n_{dc}} - U_{dc,j} \right) \qquad i = n_{dc} \tag{13}$$

The algorithm described above is now combined in a sequential AC/DC power flow algorithm that is depicted on Fig. 2.

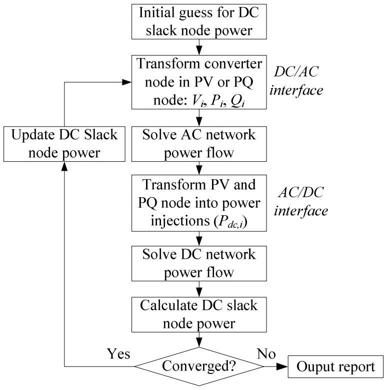
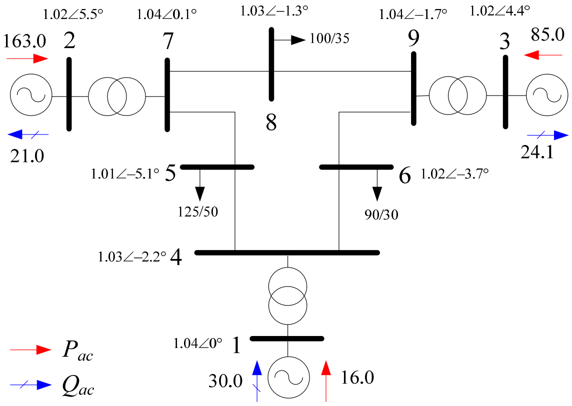


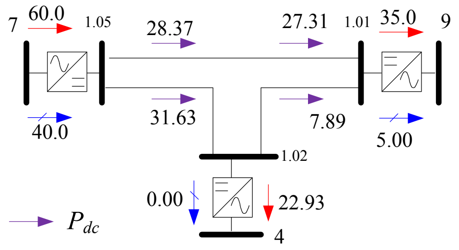
Fig. 2. Flowchart of sequential power flow for AC/DC power flow algorithm.

3. Simulation and Results

In order to demonstrate the effectiveness of the proposed AC/DC power flow approach, a MATLAB® [29] version 7.12.0.635 (R2011a 64-bit) program (*m*-file) is developed for this purpose. This algorithm is integrated with the aid of the AC power flow program *Power System Toolbox* (PST) [30], an open-source MATLAB® toolbox. Simulation is carried out on WSCC 3-machine, 9-bus system [23] with a 3-terminal MTDC network presented on [21]. The MTDC network is connected between node 4, 7, and 9. The converter station at node 4 is defined as DC slack (*Q*-mode: U_d control) to keep constant $U_{dc,3}$ = 1.00 p.u, whereas the other converter stations are used on *P-control*. The converter's data are, 100MW 2x150kV. The line resistance can be obtained from [21]. The AC/DC power flow results of the proposed approach in this paper are shown in Fig 3a and 3b.



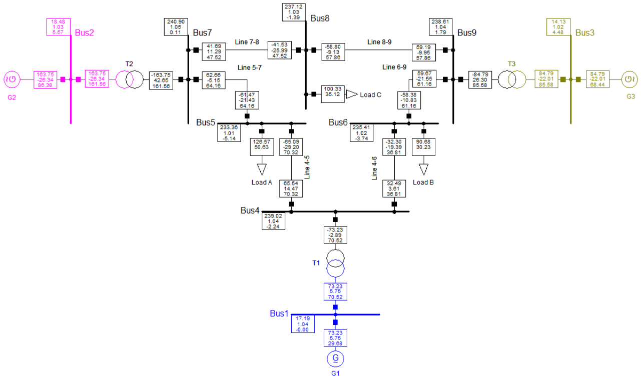
(a) WSCC 3-machine 9-bus system, AC network



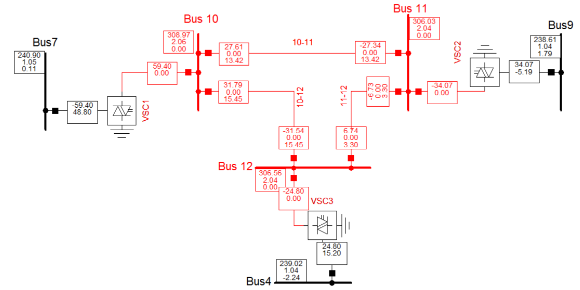
(b) Line powers an AC network injections of 3-node VSC-MTDC system

Fig. 3AC/DC power flow solution using the proposed approach.

Fig 4 shows the results calculated using DIgSILENT® PowerFactory™ v14.0.525.1 [24]. This is a simple comparison in terms of voltages and power flow that demonstrates the effectiveness of the approach proposed.



(a) SCC 3-machine, 9-bus system, AC network



(b) Line powers an AC network injections of 3-node VSC-MTDC system.

Fig. 4. AC/DC power flow solution using DIgSILENT® PoweFactory™.

4. Test Interconnection Scheme

Supergrid will be the transmission backbone of Europe's decarbonised power sector. It will facilitate the trading of electricity across and it will strengthen security of supply [9]. Although the *Supergrid* has received much attention, it cannot be materialised yet. While the basic technology might seem available, several technical limitations still exist [10]. Many *Supergrid* topologies have been proposed or studied by different organizations [31], [32], [33]. However, regulatory and policies aspects have been defined such as A single planner (European Network of Transmission System Operators for Electricity, *Entso-e*), a single operator (ISO), a single grid code (Entso-e) and a single European regulator (ACER). However, the North Sea *Supergrid* can probably not fulfil the planned criteria for an optimally operated structure [34].

The main reason, for the latter would be that independently planned projects would be attempted to be coupled together, leading to a rather grown network, comprising several DC and AC voltage levels and possibly different frequencies.

The 2030 Possible optimised integrated offshore network development based on results of Entso-e is depicted on Fig. 5. It is based on the national target in terms of offshore wind power for North Sea national, scenario 2030. This was created by *European Wind Energy Association* (EWEA), and depicted on Fig. 6.

The *Supergrid* will be materialised in phases, initially connecting the current crop of offshore wind generators to existing networks. As a first step, (Phase 1) the nodes will be built in the North Sea using 2015 technology as a means to cluster the offshore wind generation for bulk delivery. Fig. 7 shows a proposal scheme for Phase 1 of *Supergrid*

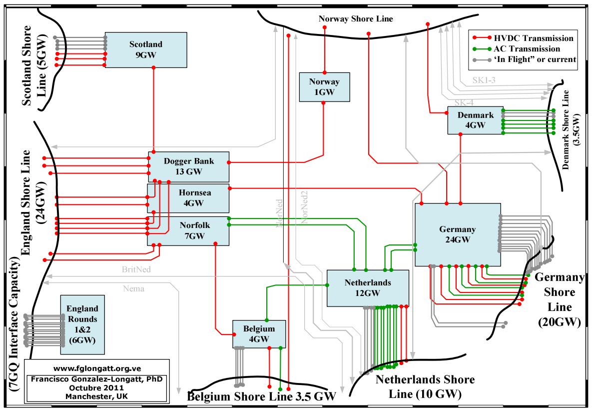


Fig. 5. 2030 Possible optimised integrated offshore network development.

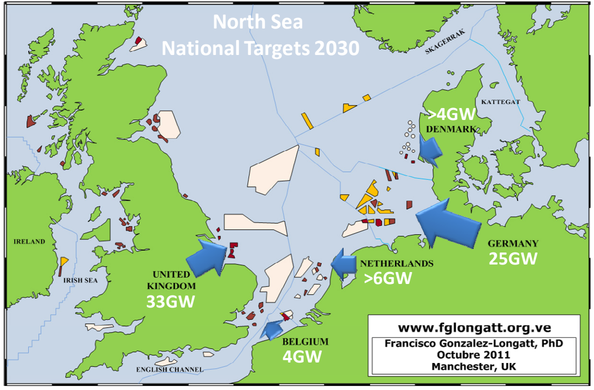


Fig. 6. North Sea National Target in terms of offshore wind power.

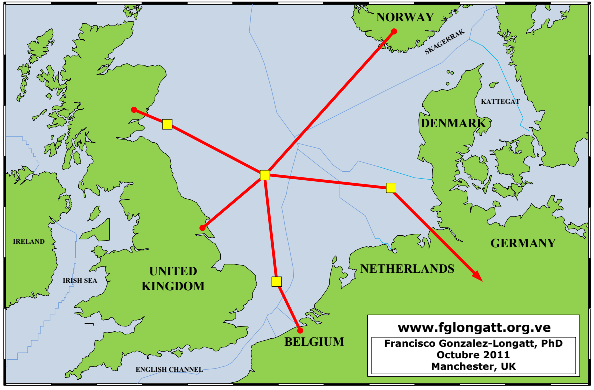


Fig. 7. *Supergrid* Phase I [35].

Energy from wind generation clusters from UK east coast will be collected at SuperNodes at Firth of Forth, Dogger Bank/Hornsea and Norfolk Bank which will be connected together and interconnected with the German and Belgian North Sea clusters as well as the Norwegian Hydro Power. The network then will deliver this power to the existing networks at terminals at Glasgow, Hull and Zeebrugge and nodes at London and Southern Germany (or North Rhine Westphalia). In this paper, the authors introduced a *benchmark test system for the Phase I of Supergrid*. The proposed test system is based on information publicly available on and this is used for the analysis of the offshore MTDC network performance.

Fig. 8 shows a summary of the AC/DC power flows expected for the different interconnections and nodes involved on the Phase I of *Supergrid.* This is a high-generation scenario based on connecting 23,000 MW of offshore wind from the Firth-of-Forth, Dogger-Hornsea, Norfolk Bank, German and Belgian Offshore clusters and using technology expected to be available between 2015 and 2020 [35]. The scenario depicted on Fig. 8AC/DC shows how the MTDC offshore transmission network is used to link the hydro resources of Scandinavia with the marine and wind resources of Northern Europe. In this case, 3.6 GW is traded between the UK area and the Norway area, depending on the electricity market. The German wind farm contributes 10GW, 1.15 GW goes to the Supergrid market, and 8.89 GW will be injected in the Germany and North Europe power system. This scenario looks unrealistic a first glance (the highest amount of wind power production) however, results demonstrate technical feasibility of heavy power flow interchanges between parties involved. Power flow injection at converter substations and undersea cables are kept below rated power.

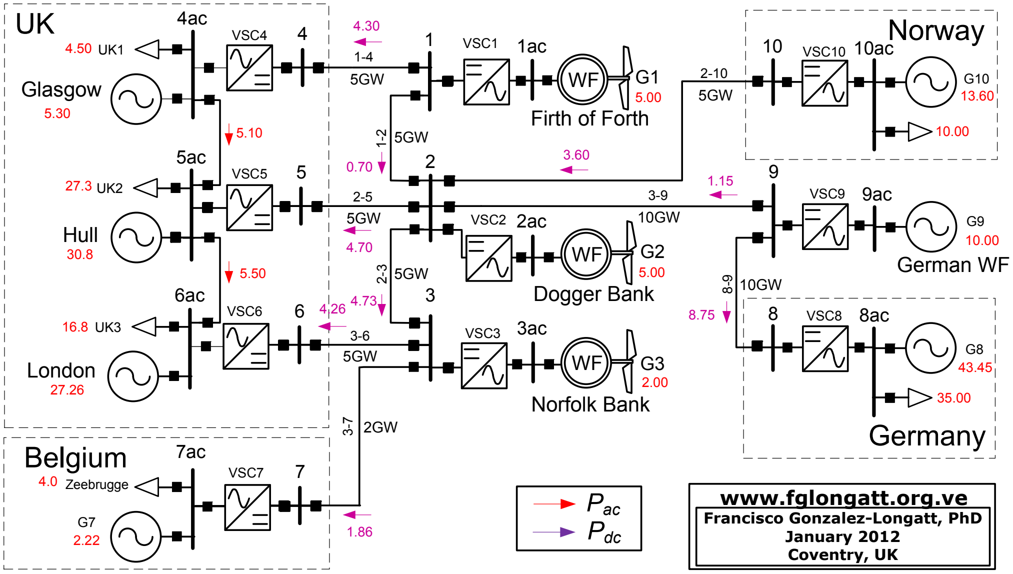


Fig. 8. AC/DC Power flow results for the benchmark test system for Phase I of *Supergrid* Project: High Generation Scenario

The results reveal an interesting technical and economic problem in terms of power losses on DC grid and converter station. The concept of unique slack bus on multi-terminal DC system creates a dilemma, which one will be DC node responsible for total power losses? This is a non trivial question and there is not straight-forward answer. There are several aspects to be considered, beyond the scope of this paper: the contracted transmission capacities, line limits and the power balance between the multiple synchronous grids are connected.

Moreover the results of this benchmark model for Supergrid Phase 1 show that the proposed method of this paper is working and provide new research direction in order to improve it.

4. Conclusion

This paper presents a sequential AC/DC power flow algorithm, which is proposed for the analysis of multi-terminal voltage source converter HVDC (VSC-MTDC) systems. The approach used is a general method for analysis AC/DC power flows including lossless VSC.The main contribution of this paper is the development of a sequential method which is easily integrated into current AC power flow programs. The method presented in this paper is implemented through MATLAB® and integrated into the Power System Toolbox (PST).

The algorithm is tested using the WSCC 3-machine, 9-bus system with a 3-terminal MTDC network and results compared with those obtained from DIgSILENT® proposed algorithm. Results of the numerical simulation on this test network show the validity of the algorithm to account for inclusion of the VSC MTDC system into an AC network.

The authors have further introduced a *benchmark test system for the Phase I of Supergrid*.The proposal of such a test system is based on information that is publicly available for the scenario presented for 2020-2025. The test system is used for the analysis of steady-state performance of the offshore MTDC network. The results of the AC/DC power flow demonstrate the capability of an MTDC offshore transmission network to link the hydro resources of Scandinavia with the marine and wind resources of Northern Europe.

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