Optimal Steady-State Operation of a MTDC system based on DC-Independent System Operator Objectives

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Abstract

This paper introduces the new concept of DC Independent System Operator, DC-ISO. The DC-ISO will be responsible for ensuring the reliability and security of the MTDC system in real-time and co-ordinate the supply of and demand for electricity, in a manner that avoids violations of technical and economic standards. A methodology for an optimal steady-state operation of a MTDC system based on DC-ISO objectives has been presented in this paper. This paper proposes the use of a type linear equality constraints based on nodal analysis to include DC-ISO operational mode to the OPF. Proposed methodology has been demonstrated and tested with a 7-node HVDC system, and results show the compromise in solutions to cope with OPF.

1 Introduction

Targets on reduction of CO₂ emissions require a dramatic reduction in electricity generation sector making really important to maximize the power contribution coming from offshore wind power plants distant from the shore. DC networks look quite attractive for the grid integration of this clean energy [1].

High Voltage DC (HVDC) transmission system based on Voltage Source Converter (VSC) enables the use of complex configuration as the multi-terminal use HVDC (MTDC) for the integration of large-scale wind power in the North Sea. Also, a pan-European transmission network is required in order to balancing and transportation of electricity in order to reach the objective of the one single European market [1], [2]. MTDC offers higher reliability, redundant and flexible technology to enable the massive integration of offshore wind power in future power systems.

The European Network of Transmission System Operators for Electricity (ENTSO-E), the association of Europe’s transmission system operators (TSOs) for electricity, recognize the importance of a pan-European transmission system to enforce energy policy goals (sustainability, competitiveness/market integration and energy security) and promote the idea of a Supergrid as an answer to European energy needs. The new Network Code on HVDC connections (NC HVDC) sets out the rules and requirements that will cover HVDC technology [3]. The NC covers HVDC connections between different parts of Europe, as well as specifying the connection rules applying to the generators, which are connected to the main electricity systems via HVDC lines. Also, the NC HVDC promotes investments in infrastructure in a non-discriminatory way, fair access to the network for new entrants and transparency in the market. These conditions make possible the rise of a new transmission system model, the DC-Independent System Operator (DC-ISO). DC-ISO is defined in this paper as a private or public entity, and it to coordinates, controls and monitors the operation of the DC transmission system involving one or several power park modules and one or several TSOs. DC-ISO is expected to perform the same functions as ISOs, but cover only the MTDC system. The DC-ISO will be responsible for ensuring the reliability and security of the MTDC system in real-time and co-ordinate the supply of and demand for electricity, in a manner that avoids violations of technical and economic standards.

The operation scope of a DC-ISO includes HVDC Systems connecting: synchronous areas or control areas, power park modules to a transmission network or a distribution network, and potentially embedded HVDC systems. Considering the possible structure of the North Sea Supergrid (NSS), it is possible to define me main concern of its DC-ISO on the MTDC system connecting offshores and onshore infrastructures, this paper is focused in this approach. Different operational control modes can be set by the DC-DC-ISO to the onshore grid side converters (GSC) due to the varying nature on power injection of the wind farm side converter (WFSC) at each offshore wind power plants (WPP).

DC voltage is the essential factor that indicates the power balance and the stability of an MTDC system. Several DC-voltage control strategies are suggested on the literature and categorized as [4]: centralized DC slack bus control, voltage margin control and distributed voltage droop control.

Voltage droop control represent a robust control scheme for MTDC systems without the need for communication systems; but this control scheme have several undesirable features: potentially higher or lower voltages during and after contingencies, it cannot cope with an outage or blocking of the DC voltage controlling converter [5], etc. Several publications [4-9] present solutions to the problem of optimal steady-state operation of the MTDC systems considering voltage droop controller [2]and others. However, the main focus of those papers is on minimizing the power losses in MTDC for large offshore wind power plants or a
transnational Supergrid.

The author accepts disbelief and even skepticism about DC-ISO concepts but recognizes a potential business opportunity for this entity on the future NSS. Several objectives (beyond losses minimization) can be identified by the DC-ISO based on the systems interactions: markets, security, offshore wind power uncertainty, etc. Virtually every single possible steady-state operating point can be objective can be optimally and centralized defined in an adequate time-scale and set-points send to the converter stations.

This paper presents a methodology for an optimal steady-state operation of a MTDC system based on DC-ISO objectives. DC-ISO might use a path inside the MTDC as interconnectors for international electricity trade allowing inter TSO operation; under this condition the power flow direction (P_d) in one or several underwater cable inside the MTDC must be loaded at very specific value under variables conditions. Also, one consequence of the losses minimization is the tendency to booster the voltage profile inside the MTDC which can create dangerous over-voltages during contingencies, DC-ISO might decide to sacrifice a small portion of the losses in order to set a voltage profile with less impact under N-1 conditions. This paper presents a combination of single-objective function and enhanced constraints solve the problem optimal operation of a MTDC system based on DC-ISO objectives.

The paper is organized as follows: Section 2 briefly defines the main considerations about DC-ISO and Section 3 establishes the short backgrounds about DC-voltage control in MTDC systems. Section 4 focuses the proposed optimal power flow in system based on DC-ISO objectives. Section 5 illustrates application examples on a representative test system of a future DC-ISO. Section 6 concludes.

2 DC Independent System Operator (DC-ISO)

One key element of the liberalization of electricity sector was separation of the control of the operation (and often the ownership) of the transmission system to ensure fair competition between generation companies requiring access to the monopoly transmission system. The US has generally followed one model for achieving this – the creation of a stand-alone independent system operator (or ISO), later also known as a regional transmission organization (or RTO). The ISO has responsibility for controlling the access to and use of the transmission grid by competing generators and retailers.

Europe has similar organizational categories to ISO, the European commission defines the term transmission system operator (TSO) as an company that is responsible for operating, maintaining and developing the transmission system for a control area and its interconnections [3].

In England and Wales a different model for facilitating competition was followed, with the creation of the National Grid Company (NGC). NGC is an independent transmission system operator (ITSO) which owns the transmission wires as well as controls their operation.

The introduction of HVDC grids brings with it major challenges, and opportunities. It has been recognized by ENTSO-E by creation of the most recent draft Network Code on High Voltage Direct Current Connections and DC-connected Power Park Modules. It establishes rules for HVDC Systems and a common framework for connection agreements between network operators and all agents involved. Network Code established that any natural or legal entity is allowed to owning or developing a HVDC System HVDC. It opens the door to promote investments in infrastructure in a non-discriminatory way, fair access to the network for new entrants and transparency in the market “[EU law 2009/72/EC]”

The most popular European Model on transmission system is the Ownership Unbundling (OU) and using this clear-cut separation two possible scenarios are possible on HVDC systems: (i) DC-Independent System Operator (DC-ISO): a fully unbundled HVDC System Operators without the grid assets (still belonging to an integrated company) and (ii) DC-Independent Transmission Operators (DC-ITO): a DC Transmission System Operator owning the assets and belonging to a vertically integrated company, with special rules to guarantee its independence.

In this paper, DC-ISO is defined as a private or public entity, and it to coordinates, controls and monitors the operation of the DC transmission system involving one or several power park modules and one or several TSOs. DC-ISO is expected to perform the same functions as ISOs, but cover only the MTDC system.

3 Voltage Control in MTDC Systems

3.1 Control of MTDC Systems

The control system for a MTDC is composed of two different layers of controllers [10], [2]: (i) terminal controllers and (ii) a master controller as illustrated in Fig. 1.

![MTDC control system hierarchy](image)

Fig. 1. Schematic representation of MTDC control system hierarchy.

The terminal controllers control the specific converters by calculating the PWM pulses for the converter bridges. Firing control is the lowest level on it and it acts very fast. Inner control, outer control and supplementary control are used for increasingly higher level functions, and have increasingly higher cycle times. The inner control or current control loop is designed to be much faster than the outer controllers. The outer controllers are the ones responsible for providing the current references signals for the inner current controller.
3.2. DC-voltage Control Strategy of MTDC Systems

Inside a MTDC network, DC control is certainly one of the most important tasks given to converter stations. A well-controlled DC on a MTDC grid requires a balanced power flow between all the interconnected nodes. There are three main DC voltage control modes used on a VSC-HVDC terminal [11]: (i) constant power mode, (ii) constant voltage mode or (iii) droop mode of control. The DC voltage versus power characteristic curve those controllers are shown on Fig. 1.

DC voltage regulator (b) node power controller (c) DC voltage droop controller

The DC voltage characteristics of constant power control mode is such that the power flow via the VSC-HVDC terminal (P) remains constant and equal to the power reference (Pref) regardless of the level of the DC voltage (U), hence the vertical characteristic line in Fig. 1(a). Constant DC voltage control mode is such that VSC-HVDC voltage level (U) remains constant and equal to the DC voltage reference (Uref) regardless of the level of the power (P). The DC characteristic curve of a constant DC voltage controller is horizontal line corresponding to the dc voltage reference (Uref) depicted in Fig. 1(b).

DC voltage droop control can be seen as a combination of the two types of VSC-HVDC controls. It tries to control power to its reference level while at the same time contributing some balancing power. Since these two actions are somewhat contradicting (i.e., power control and DC voltage control) one action happens at the cost of steady state deviations for the other. DC voltage droop characteristic is shown in Fig. 1(c). The symbol RDC refers to the DC voltage response and has the unit of MW/kV. The slope is often given in terms of the DC droop constant (ρDC), which is the ratio of change in DC bus voltage to the corresponding change in converter power both in per-units. It could also be defined as the change in DC voltage in per-unit that results in 100% change in converter power flow.

The DC voltage droop constant (ρDC) and the DC voltage response (RDC) are related to each other by:

\[ \frac{P_{\text{rated}}}{U_{\text{rated}}P_{\text{DC}}} = R_{\text{DC}} \] (1)

where \( P_{\text{rated}} \) and \( U_{\text{rated}} \) refer to rated power and rated DC voltage of the DC terminal, respectively. The relation between DC voltage and converter power at steady on a VSC-HVDC terminal using DC voltage droop control is given by:

\[ U_{dc} = U_{\text{ref}} + \frac{1}{R_{\text{DC}}} \left( P_{\text{ref}} - P_{dc} \right) \] (2)

It could be noted that the steady-state characteristics in constant power control mode and constant DC voltage control mode could be represented by DC voltage droop controllers with \( R_{\text{DC}} = 0 \) (i.e., \( \rho_{\text{DC}} = \infty \)), and \( R_{\text{DC}} = \infty \) (\( \rho_{\text{DC}} = 0 \)), respectively.

3.3. Power Flow in DC systems

Let consider a DC network which consists of \( n_{dc} \) DC nodes networks (see Fig. 1), each node is characterized by nodal voltage (\( U_{dc,i} \)), and nodal (\( P_{dc,i} \)) power injected into the DC network. The current injected is written into a matrix form [2]:

\[ \mathbf{I}_{dc} = \mathbf{Y}_{dc} \mathbf{U}_{dc} \] (3)

where the DC current vector \( \mathbf{I}_{dc} = [I_{dc,1}, I_{dc,2}, ..., I_{dc,n_{dc}}]^{T} \), \( \mathbf{U}_{dc} = [U_{dc,1}, U_{dc,2}, ..., U_{dc,n_{dc}}]^{T} \) is the DC voltage vector and \( \mathbf{Y}_{dc} \) is the DC nodal admittance matrix. The current injections \( \mathbf{I}_{dc} \) are not known prior to the power flow solution for the DC network.

\[ P_{dc,i} = 2U_{dc,i}I_{dc,i} \] (4)

The vector \( \mathbf{P}_{dc} = [P_{dc,1}, P_{dc,2}, ..., P_{dc,n_{dc}}]^{T} \), which refers to power flow into the DC grid via the DC terminals, is given by [11]:

\[ \mathbf{P}_{dc} = K_{\text{conv}} \mathbf{U}_{dc} \otimes (\mathbf{Y}_{dc}^{-1}) \mathbf{U}_{dc} \] (5)

where the symbol \( \otimes \) is entry-wise (point-to-point) matrix multiplication operator, also called Hadamard product operator and \( K_{\text{conv}} = 1 \) for a monopole converter and 2 for a bipolar [12].

3.4. AC/DC Power Flow Problem

Fig. 2 shows a general representation of a MTDC system. This system consists of \( n_{dc} \) DC nodes which are connected to the AC system using \( n_{dc} \) VSC converter stations.

Power losses at each converter stations are neglected for simplicity. Fig 3 shows a representation of loss-less VSC-HVDC converter station used on MTDC system, the main variables are depicted and references for power flow are assumed on such directions. The active power \( (P_{ac,k}) \) conservation between the AC and DC side can be written as [2]:

\[ P_{ac,k} = U_{ac,k} I_{ac,k} \] (6)

Fig. 2. Representative scheme of MTDC system connected to AC power system.

Fig. 3. Representative scheme for a VSC-HVDC converter station.
For no-over modulated lossless VSC converter \( P_n < 1 \), the relation between AC and DC voltages can be written as \[ V_{ac} = U_{dc} = P_{dc} \] (6)

For no-over modulated lossless VSC converter \( P_n < 1 \), the relation between AC and DC voltages can be written as \[ V_{ac,k} = U_{dc,k} = K_0 P_{ac,k} \] (7)

where \( V_{ac,k} \) is the real part of AC voltage, \( V_{ac} \) is the imaginary part of AC voltage, \( K_0 \) is the constant depending on the modulation method, \( P_{ac} \) is the real part of modulation index and \( P_{ac} \) is the imaginary part of modulation index.

Several publications deal with the problem of AC/DC power flows in MTDC, Temesgen et al [13], presents a numerical iteration based upon Newton-Raphson approximation for lossless converter stations using the unified approach. Beerten et al [14], [15] have used the sequential approach for the MTDC power flow problem, they have included converter losses and defining the power set-points with respect to the system bus. In [16], the concept of distributed DC voltage control for power flow is included.

4. Optimal Power Flow in MTDC Systems

4.1. Problem of OPF

Optimal power flow (OPF) is a common tool used for the optimization of a given AC power system network. The idea of an OPF algorithm is to find a set of values of the network parameters which will optimize one (or more) of the system’s functionalities [17], i.e. system power losses, total generation cost, operational limits, or system security. DC-ISO will use the OPF in order to dispatch the MTDC according to signals provided by the pool market. The steady-state behavior of a MTDC system can be described by a set of nonlinear set of the algebraic equations:

\[ G(X, Y) = 0 \] (8)

where \( G \) is the set of algebraic equations define the power balance at network buses as shown in (5), and \( X \) is a state vector and \( Y \) is the vector of independent variable. The state vector contains the state variables describing the state of the MTDC system, it contain dependent variables. DC voltages can be dependent or independent variables depending on the voltage control used. Slack node and other voltage-type nodes provides known or independent variables contained in \( Y \).

OPF is formulated mathematically as a general constrained optimization problem where set of constraints are taking in account. The most basic and general OPF formulation is based on a problem of minimization without inequality constraints as:

\[ \min f(X, Y) \] (9)

Subject to:

\[ G(X, Y) = 0 \] (8)

where \( f(X, Y) \) is the function to be optimized.

4.2. Definition of Objective Function

The problem of optimizing the performance of a MTDC system is formulated as general optimization problem. It is required to state from which point of view the performance of the system will be optimized. In the classical problem of OPF, the objective function is “to minimize the overall generating cost”

Most of the published OPF algorithms seek to optimize only one objective function, however, many other objective functions are possible [18]: minimize changes in controls, minimize system losses, maximize security, etc. After a literature review, the number of published paper contributed to the OPF multi-objective problem is small [18], and the favourite combined objectives may include, generating cost, environmental variables and security. In terms of OPF, the most used objective function is minimize the system losses as is applied on [6], [17], etc. DC-ISO coordinates, controls and monitors the operation of the MTDC involving one or several power park modules and one or several TSOs, as consequence minimize the system losses is expected to be one priority on optimal steady-state operation.

In this paper, system losses are located on the DC transmission system and it is assumed to be the Joule heating or ohmic heating in the cables. Under the previous assumption, the total losses in a MTDC system can be written as:

\[ f(X, Y) = P_{loss} = \sum_{i=1}^{n} P_{dc,i} \] (10)

where \( P_{dc,i} \) are the elements in \( P_{dc} \) calculated in terms of the nodal voltages using (5).

4.3. Definition of Constraints

The OPF in MTDC is a mathematical optimization problem, typically called constraint optimization. In this process, the objective function, \( f(X, Y) \), is optimized with respect to some variables in the presence of constraints on those variables. The constraints divide the searching space into two domains, the feasible domain where the constraints are satisfied, and the infeasible domain where at least one of the constraints is violated. In general terms, the OPF problem may include several special forms for constraints: nonlinear constraints, bound constraints, linear inequality constraints, and linear equality constraints. A description of the definition of the constraints used in this paper are presented on the next sections.

4.3.1. Bound constraints

Lower \( (X_{min}) \) and upper \( (X_{max}) \) bounds limit the components of the solution \( X \). Bound constraints are written in the form of:

\[ X_{min} < X < X_{max} \] (11)

VSC converters are used to control DC voltage inside MTDC. Those power converters, usually use IGBTs as commutation devices which are extremely sensible and have very low capacity to cope with voltages changes. DC overvoltage which may stress the commutation devices and
extremely low under-voltages can cause destructive overcurrent on the IGBT. As consequence there are limits with regard to steady state voltage ranges at the converter stations. In this paper, the \( i \)-th node DC-voltage at station converters \( (U_{dc,i}) \) are written as bound constraints based on operational limits:

\[
U_{\text{min}} < U_{dc,i} < U_{\text{max}}
\]

where \( U_{\text{min}} \) and \( U_{\text{max}} \) represent the minimum and maximum allowed voltage. The use of bound constraints allow met technical operational limits but at the same time, there is a mathematical advantages because allow to obtain faster and more reliable solutions because the searching space is reduced.

4.3.2. Nonlinear equality constraints

Nonlinear inequality constraints have the form \( G(X,Y) = 0 \), where \( G \) is a vector of constraints, one component for each constraint. The mathematical formulation of the OPF includes a set of nonlinear equality constraints as presented (8). The constraints represent the power balance at each node or power flow equations as described in (5). In most practical problems the minimum is found on the boundary between the feasible and infeasible domains, that is at a point where \( G(X,Y) = 0 \).

4.3.3. Linear inequality constraints

Linear inequalities constraints have a form as:

\[
A_{\text{ineq}} X < B_{\text{ineq}}
\]

where \( A_{\text{ineq}} \) is an \( n \)-by-m matrix, which represents \( m \) constraints for an \( n \)-dimensional vector \( X \). \( B_{\text{ineq}} \) is \( m \)-dimensional. In most optimization problems the inequality constraints prescribe limit the components of the solution \( X \).

There is a very strict current limitation on VSC converter used in MTDC systems. The power converter commutation devices, usually IGBTs, have very little, if any, overcurrent capacity. The VSC control system will make sure that the converter valves maximum current is not exceeded. Linear inequalities constraints is used in the OPF problem of MTDC to represent the maximum current limit in converters:

\[
I_{\text{conv}} < I_{\text{max}}
\]

where \( I_{\text{max}} \) represents a vector containing the maximum loading current allow in each converter station. Using the nodal analysis, the nodal current can be transformed using (3) into a set of linear inequalities constraints as follow:

\[
I_{\text{conv}} = Y_{dc} U_{dc} < I_{\text{max}}
\]

where \( Y_{dc} \) is the \( dc \) admittance matrix, \( X = U_{dc} \) and \( B_{\text{ineq}} \) as defined in (14).

4.3.4. Linear equality constraints

Linear equality constraints have a form as:

\[
A_{\text{eq}} X = B_{\text{eq}}
\]

where \( A_{\text{eq}} \) is an \( n \)-by-m matrix, which represents \( m \) constraints for an \( n \)-dimensional vector \( X \). \( B_{\text{eq}} \) is \( m \)-dimensional. The linear equality constraints are really important in this paper because allow to define one potential interest of the DC-ISO. The DC-ISO will be responsible for ensuring the reliability and security of the MTDC system in real-time and co-ordinate the supply of and demand for electricity, in a manner that avoids violations of technical and economic standards.

Let consider a massive meshed MTDC, the DC-ISO might be interested on the use of a very specific branch or a very specific path inside the MTDC system, such can be the case of define a secure path as interconnectors between international TSO to allow the international electricity trade. Under this scenario, the power flow direction and value in one or several branches, undersea cables, inside the MTDC must be loaded at very fixed and specific value under any variables operation condition. This operation mode can be transformed into linear equality constraints.

Let consider the domain of a DC-ISO inside a MTDC, and let assume the DC-ISO is interest operates a single branch between node \( i \) and \( j \) a constant current, independently of the system variations (see Fig. 4).

Fig. 4. MTDC system indicating the domain of a DC-ISO: A branch between nodes \( i \) and \( j \) is operated at constant current.

The current flowing through the cable connected between node \( i \) and node \( j \), \( I_{ij} \), is written using nodal analysis as:

\[
I_{ij} = Y_{ij} (U_{dc,i} - U_{dc,j}) = I_{\text{op}}^{\text{op}}
\]

where \( Y_{ij} \) is the correspondent element of the \( Y_{dc} \) is the DC nodal admittance matrix, and \( I_{\text{op}}^{\text{op}} \) represents the operational current defined by the DC-ISO for that specific branch.

The use of current in this constrain is preferred over power because limit the power transfer of submarine cables are typically defined by the thermal limits (ampacity). Also, the use of current on this constraints eludes the nonlinear problem created when power is used and avoid references complications related to the power direction and loses allocation in the controlled cable. It is easy to see the matrix \( A_{\text{eq}} \) is a square matrix and the number of no zero elements is twice the number of controlled branches. Linear constraints do not affect Hessians, second derivatives of the Lagrangian, allowing to save running time and memory.

5. Simulation and Results

The proposed optimal power flow in MTDC systems is tested and demonstrated in this section, a simple test system is used for that purposes. The main details of the test system are shown on Fig. 5, more details can be found on [17]. DC-ISO is responsible for ensuring the reliability and security of the 6 undersea-cables connecting 3 wind farm to 2 AC systems. Initially, classical power flow is calculated in order to see obtain the non-optimized values of the main variables. Table 1 and 2 show the results of non-optimized load flows, it is evident from the results that controlling the voltages at the two grid side converter (GSC1 and GSC2) converter the minimum losses are reached but it means a change on the power direction on cable 4-5.
Let consider DC-ISO is interested on the use the cable 4-5 to send power from AC1 to AC2. Then, the current flowing to the cable 4-5 is specified to be $I_{54}^{op} = -0.10$ p.u. Table 5 and VI shows the results of the Case B as previously specified.

Table 5. Load Flow Results for Optimized Conditions B: Nodes.

<table>
<thead>
<tr>
<th>From To</th>
<th>Case I: GSC1 V-control</th>
<th>Case II: GSC2 V-control</th>
<th>Case III: GSC1 and GSC2 V-control</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>$P_W$ (p.u)</td>
<td>$U_W$ (p.u)</td>
<td>$P_W$ (p.u)</td>
</tr>
<tr>
<td>1</td>
<td>1.09749</td>
<td>0.40000</td>
<td>1.09549</td>
</tr>
<tr>
<td>2</td>
<td>1.09738</td>
<td>0.30000</td>
<td>1.09538</td>
</tr>
<tr>
<td>3</td>
<td>1.09998</td>
<td>0.49998</td>
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<tr>
<td>4</td>
<td>1.09567</td>
<td>0.00000</td>
<td>1.09367</td>
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<tr>
<td>5</td>
<td>1.09817</td>
<td>-0.00002</td>
<td>1.09617</td>
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<tr>
<td>6</td>
<td>1.07472</td>
<td>-0.90053</td>
<td>1.07269</td>
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<tr>
<td>7</td>
<td>1.09404</td>
<td>-0.27842</td>
<td>1.09202</td>
</tr>
</tbody>
</table>

Using basic circuit theory, $I_{54} = (R_{54})^{-1}(U_{5a} - U_{5b})$, and the results shown on Table 5, it is easy to demonstrate $I_{54} = -0.10$ p.u for all considered simulation cases and as consequence it has been proven the proposed approach is correctly working. One important consequence of including the restriction of current flowing through cable 4-5 is the voltage profile is slightly lower compare with the optimize solution calculated on Case A. However, the new operational condition made impossible reach losses as obtained in Case A. Table 7 and 8 include results of the OPF considering the current flowing to the cable 4-5 is specified to be $I_{54}^{op} = +0.10$ p.u. This is the most interesting case because the operational restriction push to the maximum the voltages across the network.

Table 6. Load Flow Results for Optimize Conditions: Power flow in Branches ($P_W$) in Per Unit.

<table>
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Table 8. Load Flow Results for Optimize Conditions: Power flow in Branches ($P_W$) in Per Unit.

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<td>N</td>
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<td>1</td>
<td>0.27945</td>
<td>0.02211</td>
<td>0.27945</td>
</tr>
</tbody>
</table>

Using basic circuit theory, $I_{54} = (R_{54})^{-1}(U_{5a} - U_{5b})$, and the results shown on Table 5, it is easy to demonstrate $I_{54} = -0.10$ p.u for all considered simulation cases and as consequence it has been proven the proposed approach is correctly working. One important consequence of including the restriction of current flowing through cable 4-5 is the voltage profile is slightly lower compare with the optimize solution calculated on Case A. However, the new operational condition made impossible reach losses as obtained in Case A. Table 7 and 8 include results of the OPF considering the current flowing to the cable 4-5 is specified to be $I_{54}^{op} = +0.10$ p.u. This is the most interesting case because the operational restriction push to the maximum the voltages across the network.

The use of only one grid side converter controlling the DC-voltage in the test system make impossible to reach all the constraints at the same time. GSC1 controlling the DC-voltage at N6 made impossible the WFC3 to evacuate the $P_{WFC} = 0.5$ p.u, in fact the voltage at N3 reach $U_{max} = 1.10$ p.u, more critical situation is found when the GSC2 is controlling...
DC-voltage at N7. Controlling the DC-voltage at both GSC allows fulfil all the constraints at the same time, using the same circuital approach, it can be demonstrated $I_{dc} = +0.10$ p.u. A discussion about the optimal number of converter controlling voltage in a MTDC is beyond the scope of this paper, however, results in this specific case indicate an important relationship between the number of converter controlling voltage and the possibility of fulfil more constraints.

6. Conclusions

This paper roughly introduces the new concept of DC Independent System Operator, DC-ISO. This is a visionary concept based on a business opportunity of optimize the operation of Multi-terminal HVDC systems. DC-ISO will be a private or public entity, and it to coordinates, controls and monitors the operation of the DC transmission system involving one or several power park modules and one or several TSOs. DC-ISO is expected to perform the same functions as ISOs, but cover only the MTDC system. The DC-ISO will be responsible for ensuring the reliability and security of the MTDC system in real-time and co-ordinate the supply of and demand for electricity, in a manner that avoids violations of technical and economic standards. A methodology for an optimal steady-state operation of a MTDC system based on DC-ISO objectives has been presented in this paper. The OPF problem is formulate to minimize the total system losses and technical constraints are included (nonlinear, bound, linear inequality and linear equality constraints). A contribution of this paper is include one operational objective of future DC-ISO into the OPF.

DC-ISO might use a path inside the MTDC as interconnectors for international electricity trade allowing inter TSO operation; under this condition the current magnitude and direction in one or several undersea cable inside the MTDC must be loaded at very specific value under variables conditions. This paper proposes the use of a type linear equality constraints based on nodal analysis to include this specific operational mode to the OPF. Proposed methodology has been demonstrated and tested with a 7-node HVDC system, and results show the compromise in solutions to cope with OPF.

References


