Distributed Control of HVDC Transmission Grids

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Abstract

Priority access of renewable resources such as offshore wind recommended by European energy directives, new market models and trading the electric energy among countries lead to new requirements on the operation and expansion of transmission grids. Since AC grid expansions are limited by legislative issues and long distance transmission capacity, there is a considerable attention drawn to application of HVDC transmission grids on top of, or in complement to, existing AC power systems. Potential benefits of HVDC transmission grids includes the possibility to access remote energy sources thereby increasing renewable penetration, improving grid security and decreasing congestion in the system. However, the secure operation of HVDC grids requires a hierarchical control system to manage different functions such as voltage or power flow control. In HVDC grids, the primary control action to deal with power or DC voltage deviations is communication-free and local which can be carried out by different control schemes such as DC voltage droop control. In addition to primary local actions, the higher supervisory control actions are needed to guarantee the optimal operation of HVDC grid.

This thesis presents distributed control of an HVDC grid. To this end, three functions are investigated to be deployed in HVDC supervisory system; coordination of power injection set-points in the presence of large wind farms, DC slack bus selection and two-stage network topology identification. However, the implementation of supervisory control functions is linked to the arrangement of system operators; i.e. an individual HVDC operator (central structure) or sharing tasks among AC system operators (distributed structure). In this thesis, all three functions are first investigated for the central structure. As main contribution, this thesis presents the distributed solutions for the determined supervisory control applications. Furthermore, to study all aspects of proposed algorithms, a co-simulation platform is introduced.

In this thesis, two different distributed algorithms based on Alternating Direction Method of Multipliers (ADMM) and Auxiliary Problem Principle (APP) are used to solve coordination of power injection. However, for distributed implementation of DC slack bus, the choice of parameters for quantitative ranking of converters is important. These parameters should be calculated based on local measurements if distributed decision making is desired. To this end, the short circuit capacity of connected AC grid and power margin of converters are considered for the evaluation of converters to work as slack bus. To estimate the short circuit capacity as one of the required parameters for selection of DC slack bus, the result of this thesis shows that the recursive least square algorithm can be very efficiently used. Besides, it is possible to intelligently use a naturally occurring droop response in HVDC grids as a local measurement for this estimation algorithm. Regarding the network topology, a two-stage distributed algorithm is introduced to use the abstract information about the neighbouring substation topology to determine the grid connectivity.

Key words: co-simulation, cyber-physical system, DC slack bus, distributed control, HVDC grids, power injection, topology processor, wind farms
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Papers

List of included papers


**Author contributions**

In Paper 1, the research problem formulation and solution implementation were carried out by Babazadeh. Van Hertem and Nordström supported and reviewed the research. The paper was fully authored by Babazadeh.

In Paper 2, the general research concept was initiated and developed by Babazadeh and Mitra, whereas the article was authored by Babazadeh. The modeling and programming was done by Muthukrishnan. Larsson and Nordström supported and reviewed the research.

In Paper 3, the general research concept was initiated and developed by Babazadeh and Mitra, whereas the article was authored by Babazadeh. The modeling was assisted by Muthukrishnan. Larsson and Nordström supported and reviewed the research.

In Paper 4, the problem formulation and the solution algorithm were done by Babazadeh. The programming of the algorithm was assisted by Muthukrishnan. The paper was fully authored by Babazadeh. Nordström supported and reviewed the research.
In Paper 5, the general research concept was due to Babazadeh and the authoring was fully done by Babazadeh. Nordström supported and reviewed the research.

In Paper 6, the research concept and design of the test-bed platform were carried out by Babazadeh. The modeling has been assisted by Fidai and Nazari. Chenine provided valuable related research on test-bed. Ghandhari and Nordström supported and reviewed the research. The paper was fully authored by Babazadeh.
Publications not included in the thesis


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Bibliography
Chapter 1

Introduction

This doctoral thesis is divided into two parts. In part I, a brief introduction to the research topic, the research context and a summary of methods and findings are presented by summarizing some of author’s research articles. Then, these research articles are presented in part II of this thesis. This chapter in part I includes motivation to the research topic and the research objectives, followed by a summary of the research contribution.

1.1 Background and motivation

In the recent power system expansion driven by growing energy demand, more attention is being put on integration of Renewable Energy Sources (RES). This is tangible by the intention of the European Union to give priority access to RES or to produce 20% of its electric power demands through RES by 2020 [30]. The benefits of integrating renewable resources such as wind or solar have been justified through many researches and to some extent in real-world projects [28, 39]. One of the challenges in increasing the share of renewable production in the power system is the remote location of the resources and consequently the problem in transmitting bulk electric energy to load centers. Current AC power transmission grids operate close to their limits. However, the expansion of the AC grid involves problematic legislative rights-of-way efforts limiting the speed of expansion. The expansion is also limited by long distance transmission capacity of AC grids. Taking these challenges into account, recently there is a significant attention drawn to application of High Voltage Direct Current (HVDC) transmission grids on top of, or in complement to, existing AC transmission grids. Potential benefits of an HVDC grid as an alternative solution include but are not limited to increasing access to remote energy sources, improving power system security and decreasing congestion in the system [31, 52, 71, 84, 108].

Topologies

Several works have been carried out to investigate the proper solution for building HVDC systems or grids [20, 60, 82]. To this end, there are two HVDC technologies, based on either the Line Commutated Converter (LCC) or the Voltage-Source Converter (VSC). Based on certain parameters such as the topology of the HVDC systems, expected transfer capacity, strength of the connecting AC system or expected control functionality, a single
technology or a mix of both technologies can be used for the solution. Some examples of suggested topologies are parallel or serial point-to-point links, star and ring topologies [47]. In the literature, the term "HVDC Grid" is used for the meshed network architecture to differentiate it from the rest of topologies while "Multi-terminal HVDC" is a general term for all configurations that connect more than two converters. Regarding HVDC grid development, the VSC technology due to its power flow flexibility is the most suitable solution to build meshed topology grids [3, 47]. On the other hand, in order to transfer higher power capacity in a series link topology LCC technology is more suitable [8, 78]. This thesis focuses on meshed HVDC grids based on VSC technology. As examples of proposals and projects on HVDC grids, Supergrid (see Fig. 1.1) has been suggested to integrate Europe’s abundant offshore wind in the North Sea and Desertec similarly to harness sustainable power from the sun-rich regions [32, 96]. Along with the main objective of the bulk power transmission from generation nodes to load centers, HVDC grids are able to offer a reliable infrastructure for connected AC areas to exchange active power or control local reactive power, thereby providing ancillary services to the AC areas. These services can be offered, for example in the context of frequency control, voltage support or damping of electromechanical oscillations [7, 13, 52, 60].

![Conceptual European supergrid structure connecting renewable power sources](image)

**Figure 1.1: The European Supergrid structure [23].**

**Protection**

To make HVDC grids come to reality, there are still some challenges to be studied and solved. The configuration of the grid, vendor interoperability and standardization [4], DC breaker and protection system [52, 92, 103], ancillary services provided by the HVDC grid and finally supporting automation and communication systems dedicated for HVDC grids...
are some of those challenges. One time-sensitive constraint in the secure operation of HVDC grid is the protection system. In contrast to the conventional HVDC which do not experience a large overcurrent during the faults due to its large DC smoothing reactance, the discharge of the DC link capacitor in VSC-HVDC can lead to high levels of overcurrent. Therefore the protection system should be designed in such a way that it detects and isolates a faulty part of the system within the range of few milliseconds. Most protection schemes proposed for DC faults e.g. include algorithms that do not use DC breakers and instead trips AC breakers. As an alternative, a full-bridge modular multi-level converter can be used to interrupt the fault current and then mechanical switches isolate the fault. In all those schemes the whole HVDC system needs to be interrupted and de-energized. To avoid HVDC grid interruption and increase the availability of the whole system, schemes with DC circuit breakers have been proposed to detect and isolate the faulted segment in the DC side. This development enables to decouple the interruption of DC and AC side and therefore brings better opportunity to operate HVDC grids and AC system independently.

Control

In addition to the protection challenges, secure operation of HVDC grids also requires a hierarchical control system to manage different functions such as voltage or power flow control. In a VSC-based HVDC grid, the variation in demand and/or generation (i.e. power injection and extraction at converters) introduces DC voltage and power deviations on the DC side. The primary response to any disturbance within the HVDC grid is normally carried out by a communication-free DC voltage droop strategy where certain converters change their power set-points proportional to the deviation in DC voltage to compensate the imbalances, which is similar to primary frequency control concept in AC system. However, other different strategies for DC voltage control of HVDC converters have also been proposed and studied in literature. DC voltage droop with or without dead-band, pilot voltage droop control and adaptive droop control are some of these strategies. While some schemes such as droop with or without dead-band as well as adaptive droop proposed in are communication-free and just use the local DC voltage information to compensate the power mismatch, the pilot voltage droop method in needs to assign a global DC voltage and then communicate the value with certain converters. Similarly, Apart from the choice of conventional or advanced droop control, the optimal design of droop constants has been studied intensively as well.

In addition to primary response, similar to AC grid, the secondary control action is needed to optimally tune the DC power and voltage set-points, and prepare the system for new disturbances considering future demand, uncertainty in generation and also market signals. The design of the secondary control for HVDC grids has been approached from different perspectives such as market concerns, grid security, system uncertainties and optimization problem formulation. In most works, the formulation of secondary correction of set-points has been studied in the context of Optimal Power Flow (OPF) with various objective functions, system boundaries, constraints and optimization techniques. The combined AC/DC optimal power flow has been studied for both the non-linear and the linearized power flow equations. The objective of secondary control in literature varies
from minimizing the losses to trying to follow the AC pre-defined schedule \cite{25,43}. Optimization techniques such as second order cone programming \cite{19} and convex relaxation \cite{17} have been used to handle the non-convexity of OPF problem and the interior point method has been commonly used to solve the problem. However, heuristic algorithms such as genetic algorithm \cite{85}, particle swarm optimization \cite{88} and differential evolution \cite{74} have also been considered. Apart from the overall AC/DC OPF formulation approach to directly correct the set-points in the HVDC grid, some other works such as \cite{55,77} propose an architecture based on integral control action similar to automatic generation control (AGC) of AC grids to carry out the secondary control within HVDC grid. In \cite{5}, distributed secondary control has been studied for HVDC grids by proposing controllers which are designed on top of voltage droop controllers. The proposed control schemes bring the voltages closed to their nominal values while minimizing a quadratic cost function of injected DC currents.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{HVDC_grid_control_architecture.png}
\caption{HVDC grid control architecture.}
\end{figure}

Considering different level of control actions, a hierarchical architecture has been assumed for the HVDC grid control system \cite{45,56}. The primary control actions in HVDC grids take place at converter level and secondary control actions happen at the higher level that is referred as supervisory controller or sometime master controller \cite{43,75}. The supervisory control level manages disturbances in an HVDC grid and bridges the gap between slower AC Energy Management Systems (EMS) and fast converter controls (see Fig. 1.2). To carry out the secondary actions, similar to AC EMS, the supervisory controller requires certain applications. For example, state estimator (with bad data detection) is applied to estimate HVDC grids’ state in the presence of errors in measurements, and a network processor is used to recognize the topology of the HVDC grid and detecting islanding scenarios \cite{15,34}. However, taking into account the different control strategies in HVDC grids compared to AC grids, the new EMS applications have to be considered when designing HVDC supervisory control system. Ancillary service coordination and DC volt-
age droop gain optimizer are examples of such applications that have been proposed and studied in [6, 31, 37, 52].

Given the HVDC grid supervisory control level to coordinate between the AC energy management system and local converter controls, the implementation of supervisory control functions can be coupled tightly to the arrangement of system operators. As shown in Fig. 1.3, there are two possible operational strategies: an individual HVDC operator (central structure) or sharing the tasks among AC Transmission System Operators (TSO) i.e. distributed structure [16, 81]. Looking at possible operational strategies of HVDC grids, two points must be taken into account when designing the HVDC control schemes. First, the control needs to function properly when the coordination of converters is shared between connecting TSOs. Second, if one TSO coordinates the grid centrally, a back-up distributed coordination plan can be considered to take over the responsibility in case of central failure.

![HVDC grid operation concepts](image)

Figure 1.3: HVDC grid operation concepts: (a) central structure (an independent HVDC grid operator), (b) distributed structure.

### 1.2 Research objective

Considering the aforementioned issues, the following research question was formulated at the initial step of the thesis:

- Will distributed control of HVDC grids offer the same levels of reliability as centralized control?

Based on the research question, the following objectives were determined for this thesis:

- **OBJ1**: Identify the need of advanced control applications for an HVDC grid supervisory controller and define their requirements (in terms of computational time as well as required measurements or information).

- **OBJ2**: Develop distributed solutions for the determined control applications and investigate if they fulfill the requirements

- **OBJ3**: Design a tool that enables modeling and analysis all aspects of proposed algorithms from control, communication and power system perspectives.
1.3 Main contribution related to research objective

The structure of objectives and corresponding contributions are shown in Fig. 1.4. Regarding OBJ1, different types of control functions for the HVDC supervisory controller have been already studied such as secondary control of DC voltage, AC/DC combined power flow and state estimation [21,34,45]. However, taking into account the literature and also possible need of supervisory actions inside HVDC grids, coordination of power injection set-points of HVDC converters has been suggested as a control function in Paper 1. The requirement on how fast and frequent the application should be run, have been also addressed in Paper 1. However, the formulation of this control function or other control functions proposed in literature require two other types of functions: i) network topology processor to provide the Y matrix and grid topology and ii) a function to select the control mode of converters. Paper 2 and 5 focus on these two supplementary control functions. Paper 2 presents an online evaluation framework to select DC voltage controlling station and has investigated which parameters are needed for such a selection. Paper 2 suggested power margin of converter and short circuit capacity of connected AC grid as possible evaluation metrics. By addressing OBJ1, the type of functions, their relations, required calculation time and finally required measurements and information were determined.

Figure 1.4: An overview of thesis contributions in relation to the research objectives.
OBJ2 addressed the distributed solution and corresponding challenges for the three above-mentioned control functions as follows:

- In Paper 1, the distributed solution for the coordination of power injection was demonstrated by formulating the problem as a non-linear constrained optimization problem. Then it has been decomposed to sub-problems using the Auxiliary Problem Principle (APP) method for the distributed structure. This distributed optimization problem is solved by exchanging the required information between the AC TSOs.

- In Paper 4, the performance of the distributed solution presented in Paper 1 has been improved by formulating the sub-problems as a convex optimization problem and adopting a modified version of Alternating Direction Method of Multipliers (ADMM) to solve the problem. Furthermore, it has been shown that the distributed solution can consider and handle other important aspects such as the N-1 secure criterion and wind uncertainty in the formulation of the power injection coordination in HVDC grids.

- Paper 3 studied the practical challenges in implementing an algorithm to estimate the grid parameters that can be used for selection of slack bus. This practical aspects included non-matrix and non-complex modelling for hardware implementation, studying type of measuring points and sensitivity of algorithm to design parameters in HVDC applications. As a major contribution, it suggested to intelligently use a naturally occurring droop response in HVDC grids as a measuring point for estimating the grid parameters and consequently short circuit capacity.

- Paper 5 proposed a distributed algorithm that uses the neighboring information to determine the grid connectivity. Regarding distributed islanding detection, the connectivity problem has been formulated as a set of linear equations and solved iteratively using successive-over-relaxation method.

To address OBJ3, Paper 6 has presented a real-time co-simulation test-bed which enables the studies regarding the design, testing and implementation of real-time control and operation applications in power system. This real-time platform reflects the characteristics of the supporting Information and Communication Technology (ICT) and the physical process, as well as the interfacing devices or systems as close as possible to the real life scenarios. This platform includes real-time power system simulator, real-time communication network simulator, software-based and real interfacing devices/measurement, HVDC converter controllers and supervisory applications. The performance of the platform has been tested by a simple distributed algorithm for power sharing in Paper 6. However, the platform has also been used in Paper 2 and 3 when the practical implementation of algorithm were the issue.
Chapter 2

Research Context

This chapter is to a large extent based on the author’s contribution in the book chapter of "L. Nordström and D. Babazadeh, Cyber physical approach to HVDC grid control, In Cyber Physical Systems Approach to Smart Electric Power Grid, pages 75101, Springer Berlin Heidelberg, Berlin, Heidelberg, 2015". This partial extract is included to provide research background and context.

2.1 HVDC grids operation and control

In order to convert high voltage AC power to DC power, two technologies are available, classical Line Commutated Converter (LCC) and the Voltage Source Converter. LCC technology is designed based on a semiconductor-based switch named thyristor. Unlike diodes, thyristors need to be turned on, or fired, to start conducting current. These switches can withstand the AC voltage in either polarity. But current can only flow in one direction and can be limited by adjusting the time the thyristors are turned on. This time, or angle in a sinusoid, at which the thyristors are turned on is called the firing angle, or valve ignition delay angle, and is used to control power flow between the HVDC stations [53].

Voltage Source Converter technology is developed based on Insulated Gate Bipolar Transistors (IGBT). The IGBT semiconductor can be controlled both with regards to being turned on or off. In VSC technology, the DC current can flow in both directions. That is a benefit over the LCC technology in which the current can flow in one direction. Considering the bi-directional capability of the DC current flow in VSC, there is no need to change the DC voltage polarity of the converters to change the power flow direction between converters. Compared to LCC technology, it is possible for VSC to be connected to weak grids which has low short-circuit level [107]. In contrast to LCC, VSC has two degrees of control which enables control of the active and reactive power separately. This control freedom comes from controlling the VSC using the Pulse Width Modulation (PWM) technology [38,14]. However, one challenge with IGBT based VSC is that they have less overload capability compared to LCC [66]. Taking into account the flexible power flow control of VSC technology, it is a recommended technology for the meshed topology HVDC grids. Therefore,
this section studies the VSC-based HVDC grid.

2.1.1 HVDC grids control system

In this section a possible control system for future VSC-based HVDC grid is described. The HVDC grid control system can be presented by two general levels: converter station control level and system control level. As shown in Fig.2.1, the converter station control consists of inner and outer control layers. The phenomena within inner or outer control layers takes place in the range of respectively milliseconds and several of milliseconds to seconds. Control functions at the station level control layer such as voltage or AC frequency stability considerations or even local power flow calculation can be implemented with delays up to a few seconds. The comprehensive description of converter control level is presented in the next section.

The system control level can be designed in different ways based on the market, technical and political consideration which brings different data exchange limitations. For example,
the control of HVDC grid can be merged with the connected AC grids and a super hybrid AC/DC operator manages the entire system [25,89]. However, as an alternative, an individual HVDC supervisory management system can be introduced to control the phenomena in an HVDC grid and bridges the gap between slower AC EMS and fast converter controls [78,81,91]. In comparison to converter level, when it comes to supervisory control, based on communication infrastructure, the requirements for control functions can vary from tens of milliseconds for wide area protection system to minutes or longer for tertiary power flow control. A simple schematic of HVDC grid control architecture involving a separate HVDC supervisory control is presented in Fig. 2.1.

Given a separate HVDC supervisory controller, it consists of state estimation application that estimates the state of the power system in the presence of errors in measurements. State estimation also includes bad data detection to detect and identify the measurements with error. Furthermore, the supervisory control requires a network processor to recognize the topology of the HVDC grid and also detect islanding scenarios. The output of the network processor can be used in state estimation or control application to form the admittance matrix. Supervisory control is also responsible for real-time balancing in HVDC grids. This can be carried out through power flow calculation after a disturbance, after a change in HVDC grid topology or periodically.

2.1.1.1 Converter control level

In the literature, two different approaches have been introduced to control the VSC, i.e. direct control and vector control. Direct control is based on controlling the voltage in the VSC. This means by controlling phase angle and amplitude of the voltage transmitted active power and reactive power is controlled. Vector control on the other hand sets the converter to work as a controllable current source. The vector control method has some advantages compared to direct control. This includes better power quality since it is less influenced by grid harmonics and disturbances. Besides, in vector control decoupled control of active and reactive power is possible. Finally it also provides the capability of inherent protection during over-current events [38,78].

In vector control approach, converter is set to work as a controllable current source. In this approach, the injected current vector is set to follow a reference current vector. Therefore, each VSC needs to have an internal current controller. In this scheme, $dq$ reference frame is used in order to project current vector into $d$ and $q$ axes (i.e. $i_d$ and $i_q$) and respectively, decouple the control of active and reactive power [51]. Assume a typical VSC station shown in Fig. 2.2. R and L are the resistance and inductance, respectively, on the AC side of the converter. These resistance and inductance consists of the transformer and phase reactor parameters. Considering this model, the equation of the AC side in $abc$ coordinates can be written as:

$$v_{abc} - u_{abc} = L \frac{di_{abc}}{dt} + R.i_{abc} \tag{2.1}$$

Where $u_{abc}$ is the voltage at point of common coupling, $v_{abc}$ is the converter’s AC voltage and $i_{abc}$ is the current flow. To follow the vector control approach, the representation in $abc$ coordinates can be transformed to $dq$ coordinate based equation [22].
In these coordinates, both $i_d$ and $i_q$ currents can be controlled separately by inner controller which leads to the decoupled control of active and reactive power in the converter. The complete block diagram of an inner current controller is presented in Fig. 2.3. The inner controller follows the reference set-points that are ordered by outer controller (i.e. $i_{d}^*$ and $i_{q}^*$).

The outer controller can control reactive power (or AC voltage) on the AC side and active...
power (or DC voltage) on the DC side. The outer controller provides the inner controller with the reference current values in $dq$ coordinate (i.e. $i_d^*$ and $i_q^*$). This controller is slower than the inner controller. Usually the PI controller is used in industrial applications due to its simplicity. However, to control the power flow in the HVDC grid, different strategies can be used to set the DC voltage and power of the outer control loop on the DC side. These strategies basically define the primary reaction of converters to any disturbance in the HVDC grid. In the next section, some of those strategies are presented.

### 2.1.2 Primary control strategies for DC voltage and power

In HVDC grids, real-time mismatch of power injection can be compensated by the DC voltage controlling converter(s). Similar to frequency in AC grid, the DC voltage deviation is a local indication of a power mismatch in an HVDC grid. The control of DC voltage at the grid level and the corresponding power flow control can be influenced by different voltage control schemes at the converter level. There are several control schemes suggested in literature to maintain power balance within the HVDC grid. In this section, the two most popular and most referenced control schemes are presented, namely the voltage-margin method (VMM) and voltage droop control.

#### 2.1.2.1 Voltage margin method

In the voltage margin method, one converter is set to control the DC voltage in the HVDC grid (i.e. like a DC slack-bus) and the remaining converters are set to active power control [54]. The $V_{dc} - P$ characteristics of this converter is presented in Fig. 2.4. When the converter operates on the B-C-D line, it is on constant DC voltage mode, i.e. $V_{dc} = V_{dc}^{ref}$. In A-B mode the converter acts as an inverter and is in constant active power level, i.e. $P_{ac} = P_{ac}^{min}$. In D-E mode the converter acts a rectifier and $P_{ac} = P_{ac}^{max}$.
In the HVDC grid with voltage-margin method, once the converter hits the limits and goes from constant DC voltage mode to constant power mode (i.e. B-C-D line to A-B or D-E line), another converter needs to work in DC voltage control mode to maintain the voltage levels in the entire grid. This can be achieved by having the other converters operating at different reference values (see Fig. 2.4), thus establishing a voltage margin between the converters. As shown in Fig. 2.4 when converter 1 reaches the minimum active power level, \( V_{dc}^{min,1} \), the DC voltage increases to \( V_{dc}^{ref,2} \), and converter 2 is now responsible to maintain the DC voltage level.

2.1.2.2 DC voltage droop method

In this method, some converters are assigned to change the injected active power based on the local deviation of DC voltage in order to provide the active power balance in the HVDC grid [20]. Different types of voltage-power characteristics have been considered in literature. As an example, in DC voltage droop without dead-band the operating point of the power injection changes as a linear function of the local voltage change (see Fig. 2.5a). To avoid changes in power injection set-point due to small changes in the DC voltage, droop with dead-band is used (see Fig. 2.5b). When it comes to DC voltage droop concept, it is communication free during the operation. The droop setting and/or new set-points can be calculated by higher level control functions such as optimal power flow at EMS/SCADA every few hundred seconds or minutes and then be sent to converters.
2.2 Short circuit capacity estimation for HVDC application

The estimation of the AC grid parameters (i.e., SCC) connected to an HVDC system can be used to adjust the converter control parameters or to select the converter’s operational control mode. Fast and accurate estimation of the grid parameters can also lead to more autonomy in terms of control adjustments. There are different passive and active methods available to estimate the SCC. Extended Kalman Filter (EKF) as a passive method provides various benefits such as cancellation of different types of noise, no forced grid disturbance and also proven experience in other applications. However, it requires high computational power due to the calculation of the Jacobian matrix. Furthermore, the convergence depends on the choice of the initial values [62]. When the predict and update functions of a state space model are non-linear in nature, EKF algorithm performs poorly. The modified version of EKF, i.e., Unscented Kalman Filter (UKF) is developed to deal with the non-linearity of the models. UKF also shares the same advantages and disadvantages of EKF in terms of implementation [67].

Considering certain requirements for the practical implementation of the algorithm such as computation, operational complication and accuracy, Recursive Least Square (RLS) can be an alternative choice for the SCC estimation. The RLS algorithm forms a regression problem using algebraic complex equations with an objective of minimizing the error between the estimated parameters and the calculated parameters based on the measurements. This regression problem is solved recursively in a discrete domain. This algorithm benefits from the low computational efforts and the possibility of non-complex and non-matrix transformation for easy hardware implementation. However, it requires two operating points to converge. The brief description of the algorithm is provided here.
2.2.1 Recursive least square algorithm

The recursive least square algorithm has been mainly used to estimate short circuit capacity in distribution networks with high penetration of renewable generations [29]. This section on RLS algorithm has been provided from the author’s previous conference paper that is not included as the contribution in the thesis [14].

![Figure 2.6: Equivalent circuit](image)

Fig. 2.6 shows an AC equivalent circuit for the connected AC grid that can be seen from the point of common coupling (PCC) at each converter. This equivalent model is considered for the RLS algorithm. In steady state conditions,

\[ V = IZ + E \]  

where \( V \) and \( I \) are the voltage and current at PCC, \( Z \) is the equivalent grid impedance and \( E \) is the equivalent grid voltage. All the parameters are expressed as complex numbers in the \( dq \) reference frame. Note that \( V \) and \( I \) are measured parameters, and \( E \) and \( Z \) are estimated parameters. Considering \( n \) different operating points,

\[
\begin{align*}
V_1 &= I_1Z_1 + E_1 \\
V_2 &= I_2Z_2 + E_2 \\
&\quad \vdots \\
V_n &= I_nZ_n + E_n.
\end{align*}
\]

Assume that the grid is stationary during the measurements, then \( Z_1 = Z_2 = \ldots = Z_n \) and \( E_1 = E_2 = \ldots = E_n \). Hence, two constant parameters \( Z \) and \( E_0 \) can be assumed for all such operating points. Considering the stationary situation, equation (2.4) can be expressed in matrix form as

\[
Y = AX
\]

where,

\[
Y = \begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{pmatrix}; \quad A = \begin{pmatrix} I_1 & 1 \\ I_2 & 1 \\ \vdots & \vdots \\ I_n & 1 \end{pmatrix}; \quad X = \begin{pmatrix} Z \\ E_0 \end{pmatrix};
\]

15
To estimate the parameters $Z$ and $E_0$ from equation 2.4, a minimum of two operating points in a stationary grid is required. Equation 2.4 is a linear regression problem expressed in the complex plane. Consider $e$ as the error between the estimated voltage and the actual measurement:

$$e = A\hat{X} - Y$$  \hspace{1cm} (2.6)

where $\hat{X}$ is the estimated grid parameter. The best-fit for the estimated parameter vector $\hat{X}$ can be found by minimising a positive function of error magnitude ($J$):

$$J = |e|^2 = e^T \cdot e = (A\hat{X} - Y)^T \cdot (A\hat{X} - Y)$$  \hspace{1cm} (2.7)

$$\frac{\partial J}{\partial \hat{X}} = 0 \quad \Rightarrow \quad \hat{X} = (A^T \cdot A)^{-1}(A^T \cdot Y)$$  \hspace{1cm} (2.8)

Equation 2.8 provides an optimal off-line estimation after all measurements are available. In order to estimate the parameters, the problem is needed to be transformed to a recursive problem using the following equations:

$$P_k = ([A^T]_k[A]_k)^{-1};$$  \hspace{1cm} (2.9)

$$B = \left( \begin{array}{c} I_k+1 \\ 1 \end{array} \right)$$  \hspace{1cm} (2.10)

$$W^{k+1} = P_k B(I + B^T \cdot P_k B)^{-1} = P^{k+1} B$$  \hspace{1cm} (2.11)

where, $P^k$ is cross correlation matrix and $I$ is the identity matrix. $B$ and $W^{k+1}$ are the intermediate variables and $I_{k+1}$ is the measured currents at iteration $k + 1$. As shown in [29], considering intermediate variables, the problem can be iteratively solved by:

$$\left( \begin{array}{c} \hat{Z}_{k+1} \\ \hat{E}_0_{k+1} \end{array} \right) = \left( \begin{array}{c} \hat{Z}_k \\ \hat{E}_0_k \end{array} \right) + W^{k+1} e^{k+1}$$  \hspace{1cm} (2.12)

where, $\hat{Z}$ is the estimated grid equivalent impedance, $\hat{E}_0$ is the estimated grid equivalent voltage and $e_{k+1}$ is the error between the measured PCC voltage and the calculated PCC voltage based on estimates. Equation 2.12 provides a straightforward method to recursively estimate the equivalent impedance and voltage. Fig. 2.7 shows the final flowchart for this recursive algorithm. The RLS algorithm can thus estimate the equivalent grid voltage and equivalent grid impedance at the PCC. In addition, thanks to the small dimension of the regression problem, the matrix inversion during computation of $W^{k+1}$ reduces to a complex number inversion which implies low computational requirement of the algorithm. As presented in Fig. 2.7, the initial values $P_0$ and $\hat{X}_0$ are required and can be found from an off-line identification. Furthermore, an evaluation can be incorporated to find whether the grid parameters have changed by time. This evaluation is based on equation 2.13 where $n$ is the moving window of the terms.

$$\tau_k = \frac{1}{2k} \sum_{i=k-n}^{k+n} \frac{||V_i - I_i\hat{Z}_i - \hat{E}_i||^2}{|I_i|^2}$$  \hspace{1cm} (2.13)

The evaluation parameter at time instant $k$ is given as $\tau_k$. The iteration variable $i$ computes the summation in a loop throughout the window $n$. The threshold for the evaluated
parameter $\tau_k$ is $\tau_\gamma$. If $\tau_k$ is greater than the threshold (i.e. $\tau_k > \tau_\gamma$), the grid parameters have changed to such extend that a new SCC estimation must be carried out. Therefore, the estimated grid equivalent voltage and impedance are no longer correct and $C_k$ must be reset to its initial value.

### 2.3 Tools for simulation of cyber-physical systems

To study the distributed control applications needed for future HVDC grids, simulation that considers all aspects of the involving systems is necessary. This section describes the modelling of distributed control for HVDC grids from a Cyber-Physical System (CPS) perspective. The term cyber-physical system is recently being used to refer to systems in which the computational entities including control/communication units (cyber) as well as physical processes are strongly coupled [68]. The integration of ICT system with traditional power system is more noticeable nowadays by implementation of new control and monitoring applications based on new technologies like Phasor Measurements Unit (PMU). The detailed study of cyber-physical systems to e.g. understand the interdependency of these sub-components and their impact on the overall quality of the system requires a multi-domain simulation tool or a co-simulation platform. Present simulators are limited by the fact that none of them can be used to carry out the detailed modelling of all the domain. In addition, developing such a simulator requires a huge investment. On the other hand, co-simulation is a solution that runs each part of the model in its relevant simulator and then coordinates all these simulators in terms of data exchange and time synchronization.

Several studies have been carried out to implement the co-simulation through different approaches. The Electric Power and Communication Synchronizing Simulator (EPOCHS) has been designed based on federated simulation with multiple discrete-event and continuous time simulators [63]. In this approach, a mediator software is used as an interface which
enables the simulators to exchange data periodically and synchronize them. It integrates
the PSLF as an electromechanical transient simulator, the PSCAD/EMTDC as an electro-
magnetic transient simulator, and the NS2 as a communication network simulators in such
a way that their internal time clocks progress simultaneously. In this approach, events are
stored in an event queue and are executed only at the next synchronization point thus accum-
ulating errors. On the other hand, Global Event-driven Co-Simulation (GECO) consists
of a global event queue to store the interleaved simulation events from power system and
communication simulators and process them in chronological order [72]. Events generated
can be executed with minimal delay.

In comparison to this method, The Discrete Event System Specification (DEVS) method
does not federate, instead, it requires continuous time simulations such as power system
should be transferred into discrete events by using different state event detection mecha-
nisms such as zero crossing [79]. This is a tedious work and one of the DEVS drawbacks.
MOSAIK as an open-source discrete event simulator have been proposed in which the ex-
ecution of simulations is performed in an event-based manner [85]. The APIs of simulators
are language agnostic and this reduces the learning overhead with new tools. All the men-
tioned approaches do not aim for hardware-in-the-loop tests. On the other hand, the Virtual
Grid Integration Laboratory (VirGIL) is proposed very recently as a modular co-simulation
platform which can be extended to have a Hardware-in-the-loop implementation [87]. It
is based on industrial grade standard, Functional Mockup Interface (FMI), that brings the
modularity feature. Any FMI compliant simulator can be integrated to work with VirGIL.
A master algorithm coordinates data exchange. The drawback is that only static analysis
for power systems can be carried out as developing FMI interfaces for dynamic analysis is
complicated.

2.3.1 PSMIX real-time co-simulation platform for HVDC grid stud-
ies
The Power System Management and Information eXchange (PSMIX) is a real-time co-
simulation platform that make it possible to study the design, testing and implementation
of real-time applications for control and operation of a power system. PSMIX real-time
platform mirrors the characteristics of physical process, ICT system and the interfacing
devices or systems as close as possible to the real life situation. PSMIX is a general real-
time architecture that can be re-configured for different studies from wide-area monitoring
and control of power transmission system to distribution grid control scenarios [10, 12].
This platform comprises of real-time power system simulator, real-time communication
network simulator, supervisory control applications, and software-based or real interfacing
control/measurement component. The key factors that can impact the overall performance
of any such real-time platform is accuracy of the software-based replications of the real
devices and the implementation of industrial automation protocols. For HVDC studies, the
PSMIX platform is set-up to simulate the HVDC grid and its supporting control and com-
munication system (see Fig. 2.8). The detailed information of the components is described
as follows.
2.3.1.1 Real time power simulator

The eMEGAsim is a commercial real time simulator which combines electrical circuit solvers, SimPowerSystem, distributed processing software and hardware for high speed real-time simulations of power system for both steady state and transient analysis. This simulator can be customized to meet I/O requirements enabling the Hardware-in-the-Loop (HIL) simulations. The simulator used in PSMIX is able to simulate the Cigre DC grid test system with the time-step of 50 $\mu$s using the average model of converter (not switching model).

2.3.1.2 Measurement units

The HIL feature of the real time power simulator enables the simulated power system to interact to outside word via different means such as analog I/Os. Since the HVDC controller is able to communicate with specific analog I/Os, a special DC measurement unit (DMU) can be developed inside the OPAL-RT simulator to send/receive the DC voltage and active power measurement with specific accuracy to/from analog I/Os. The I/Os have 16-bits resolution. The I/Os use EtherCAT protocol to communicate. For the AC side, a Software-based Phasor Measurement Unit (SoftPMU) or a real PMU device can be considered (detailed information has been presented in [12]).

2.3.1.3 HVDC industrial controller

In this type of real-time platform, an industrial HVDC controller can be used. For the purpose of this thesis, the controller that runs Windows embedded integrated with INtime reliable real time operating systems (RTOS) has been considered. This controller communicates with the analog device via EtherCAT protocol. The data exchange among the HVDC control substations are carried out via Ethernet or UDP protocol.
2.3.1.4 OPNET communication network simulator

In the real-time platform, any communication network software-based simulator with the ability of connection to real-world and real-time capability can be considered to model and study the communication aspect of the understudied system. However, this can be extended to real-time commercial network emulators as well. In this thesis, OPNET has been considered as a communication system modeler to provide comprehensive development environment for modeling and studying communication networks. OPNET solution provides the System-in-the-loop (SITL) module enabling the connection of the simulation model with live network hardware [12].

2.3.1.5 Supervisory applications

The application component of the PSMIX platform consists of openPDC as the phasor data concentrator and the KTH PowerIT as the application hosting platform that connects to openPDC to receive the synchronized measurements [27]. Besides, it is able to receive the HVDC grid information i.e. DC voltage and active power from the converters using industrial defined Ethernet protocol. Several applications have been implemented in PowerIT platform, such as average frequency visualization and electro mechanical mode estimation for AC grid, and monitoring and control application for HVDC grid. Note that for distributed schemes, there is no need of a centralized application to be run on the PowerIT platform.
Chapter 3

Related Works

This chapter presents the related works that are directly relevant to studied control functions. Therefore, the related work is divided into three categories; first the works that cover optimal power flow in HVDC or hybrid AC/DC grids. Second, the work related to HVDC converter control mode selection algorithm including its parameter’s estimation algorithm. Third, the works related to network topology processing architecture and design.

3.1 Coordination of power injection

Normally the primary control action to small disturbances in the HVDC grid takes place by communication-free schemes such as DC voltage droop control. However, the secondary control is needed to optimally tune the DC power and voltage set-points, and prepare the system for new disturbances considering future demand, wind uncertainty and also market signals. In most works, the formulation of secondary control of set-points has been studied in the context of Optimal Power Flow (OPF) with various objective functions, boundary of the system, constraints and optimization techniques. Several researches have presented the combined AC/DC optimal power flow solutions for single AC grid with embedded MTDC networks or an HVDC grid connecting different AC areas. In [9], a comprehensive tool for solving OPF in hybrid AC/DC systems for grid integration of large offshore or onshore wind power plants has been presented. The power flow of AC and DC side have been linked through an equation on the power balance in the converter \( P_{AC} = P_{DC} - P_{loss,converter} \). Similarly, the work in [25] tackled the combined AC/DC problem but with extra constraint on DC current and voltage. These constraints come from considering two different VSC control strategies, i.e. constant DC voltage control (master-slave control) and DC voltage droop control in the formulation. Since in the practical implementation of HVDC grid, there might be various types of non-linear DC voltage droops, [100] proposed a generalized OPF algorithm that considers those control modes also. In these works, the objective function usually covers the transmission and converter losses in both AC and DC systems as well as generations costs. Since most of the works on combined AC/DC OPF (with similar formulation as [9,25]) do not guarantee to obtain the global optimal solution, [7,19] have aimed to determine the global optimal
solution by using convex relaxation techniques and transform the optimization problem to a semidefinite program or second-order cone programming.

Apart from the type of formulation, some works have separated the combined AC/DC calculations to different parts to optimize the computational efficiency. For example in [18], the system is divided into two sub-systems: 1) the HVDC grid and the AC area connected to slack converter of HVDC grid 2) the rest of AC area. The problems in these two subsystems are solved in an iterative way. The decomposition of AC/DC power flow has also been analyzed in [73] based on network decomposition concept. In this approach, an AC grid OPF calculator solves the problem for the AC area, the DC grid OPF calculator solves for the HVDC grid and a master coordinator handles the data exchange between different calculators.

Given the separation of calculation in some works, they still focused on the centralized combined AC/DC power flow with one single entity or operator. However, a valuable study has been carried out in [64] to introduce a distributed power flow formulation for multi-area AC systems with embedded HVDC systems. In this work, three operational schemes are considered: 1) whole power system is operated by one single operator, 2) in addition to the AC operators, the HVDC grid is operated by a separate operator 3) there is no HVDC grid operator and areas are separated based on their geographical borders and each area includes the corresponding AC and part of HVDC system. The proposed distributed method for scheme 2 and 3 is compared with the central approach in scheme 1 where there is a single operator to dispatch the set-points. The converter is modeled as a generating unit with positive or negative value based on the direction of power flow. The shared variable between areas are power exchanges on both HVDC links and AC lines that connect two areas. Therefore the objective function includes three parts; 1) the cost of AC generating units, 2) power losses and 3) a penalty for the shared variable. In the problem formulation, multi-area power systems are synchronous, that means the areas are interconnected by AC and DC links or grids. Besides, a simplified linear model is used for AC power flows based on deviation of angles and for DC power flow based on deviations of DC voltages. This work does not include security-constrained optimal power flow. The idea of having individual operator for HVDC grid has also been presented in [50] and a simple OPF has been introduced for an HVDC grid with the objective of minimization the DC losses.

All previous mentioned related works formulate the OPF in a way that the generation (e.g. wind power production both in AC or DC grid) and the demand from the AC grid are assumed to be known. This means they emphasize on a deterministic set-up and do not take into account any uncertainty in their formulation. However in [102], uncertainty in the generation and security constraints have been considered in a linear AC/DC power flow formulation where the AC voltage angles and the DC voltage magnitudes are eliminated.

As can be seen, these related works have approached the power flow problem in HVDC grids or hybrid AC/DC grids from several angles such as the boundary of the system, efficiency of algorithm and type of formulation (see table 3.1). In relation to these related works, paper 1 has first proposed a separate power injection coordination for HVDC grids with large wind offshore. This coordination is a bridge between slower overall AC/DC power flow calculator and fast primary control actions at the converter level. It aims at finding an optimal operation point within the HVDC grid especially during large wind disturbances while it tries to follow the converters’ schedules set by the connecting AC-TSOs.
Table 3.1: The references and their OPF problem areas

<table>
<thead>
<tr>
<th>operational strategies</th>
<th>system configuration</th>
<th>type of formulation</th>
<th>other consideration</th>
<th>N-1 criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single AC/HVDC operator</td>
<td>HVDC and AC operators</td>
<td>embedded AC/HVDC and synchronous AC/HVDC</td>
<td>central</td>
<td>distributed</td>
</tr>
<tr>
<td>Baradar [18]</td>
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<tr>
<td>Aragües [9]</td>
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<tr>
<td>Baradar [19]</td>
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<td>Liu [33]</td>
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<td>Gonzales [30]</td>
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<td>Wang [100]</td>
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<td>Wiget [102]</td>
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<td>Iggland [65]</td>
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</table>

every 15 – minutes. Paper 1 also has aimed to show through a sensitivity analysis that HVDC grids benefit from this type of coordination when they are subjected to variation of wind production. Furthermore, the requirement for the updating interval of power injection coordination have been studied which can be an interesting information for all related works to check the efficiency and speed of their algorithm. Based on this time requirement, as the main contribution paper 1 has proposed a fully distributed algorithm based on the auxiliary problem principle to divide this coordination among the connecting AC TSOs. Paper 4 has completed the idea in paper 1 by considering the wind uncertainty and N-1 criterion in the formulation of distributed coordination. However, paper 4 has improved the efficiency of the distributed coordination by creating convex subproblems and using the ADMM method to solve them.

3.2 DC slack bus selection and related practical implementation

The concept of slack bus in AC power system problems is a mathematical requirement to absorb all the resulting uncertainty of the solution but it has no physical interpretation to any generator bus. Research in [33] addressed the mathematical challenges introduced by the slack bus in AC load flow solutions with uncertain nodal powers. However, in the context of HVDC grid, DC slack bus is a physical HVDC converter controller needed to be set in term of its controlling modes. A comprehensive study on classification of DC voltage nodes and possible HVDC grid control strategies in [38] suggests that the future HVDC grid comprises of different complex voltage controllers including a DC slack bus. The effects of DC voltage control strategy on the dynamic behavior of bus voltages have been studied through simulations for a multi-terminal HVDC following a system disturbance in [49] and after a converter loss in [48]. Two different DC voltage control methods are simulated in these papers: voltage margin method and DC voltage droop method. However in [35], the effect of droop setting on the post-outage steady-state have been mathematically assessed and some suggestions have been made on assigning the DC voltage droop values. Furthermore, as a general note, [35] has expressed that sensitive voltage controllers (i.e. the one connected to weak grid) may have disadvantages for system stability and should be investigated.
Given a slack converter in an HVDC grid control architecture, requirements for selecting the specific converter to take the role of a DC slack bus may be considered in static planning problem. The off-line selection of DC slack bus in the planning phase is a matter of optimization which takes time and requires careful consideration. However, the online selection of slack bus is needed and can be significant after loss of the slack converter in an HVDC grid. To this point, it seems to be a gap in the literature on how to determine the validity of converters to act as the DC slack bus in the HVDC grid and what parameters to be considered for this online validity check. Therefore, paper 2 presented a real-time evaluation framework to choose the appropriate DC slack bus in an HVDC grid. This online quantitative evaluation examines the post-contingency capacity margin of the converter and the strength of all AC grids connected to converters (characterized by grid’s short circuit capacity). Paper 3 studied different aspects of implementing recursive least square algorithm as a potential candidate for the estimation of SCC for the DC slack bus evaluation.

There are passive and active methods to estimate grid parameters to calculate the short circuit capacity. Passive methods use disturbances present in a grid to estimate the grid parameters, whereas in active methods, the grid is disturbed along with its normal operation. There are also quasi-passive methods which usually requires the change in the operating point of the power converter [29, 95]. The comparison of the Kalman filter and the Recursive Least Squares (RLS) algorithms as two examples of passive and quasi-passive methods for the estimation of the grid impedance has been studied in [50]. The estimation of the equivalent grid impedance seen from a power converter connected to the real electric distribution network using Extended Kalman Filter (EKF) is addressed in [61]. The study has focused on the typical low voltage distributed power generation networks where the grid impedance is (in most cases) inductive-resistive. Other related work on EKF in [62] have presented various benefits of the algorithm such as cancellation of different types of noises, no forced grid disturbance and also a proven experience in other applications. However, this paper as well has shown the challenges regarding EKF such as need of high computational power due to the calculation of the Jacobian matrix and also the dependency of convergence on the choice of the initial values. In addition, when the predict and update functions of a state space model are non-linear in nature, EKF algorithm performs poorly. In [67], a modified version of EKF, i.e. Unscented Kalman Filter (UKF) has been developed to deal with the non-linearity of the models. However, UKF algorithm also shared the same advantages and disadvantages of EKF in terms of implementation.

Given either of these methods to estimate the grid parameters, accuracy and sensitivity of the estimation algorithm to the system operational changes and computational requirements are also of importance, especially when it comes to real-life implementation of the algorithms. Therefore, Paper 3 tries to fill the gap in the literature on studying the operational and practical challenges in the implementation of the SCC estimation algorithm focused on the RLS method. Since RLS algorithm needs at least two operating points for estimation, as the major contribution, paper 3 proposes to intelligently utilize a naturally occurring disturbance in HVDC grids to use as the second operating point to obtain a fairly correct estimate of SCC. This paper also has studied the practical aspect of the estimation algorithm regarding the selection of operating points. Furthermore, the original algorithm has been also reformulated and simplified to make it non-complex without the
use of matrices, in order to be able to implement on an industrial real-time controller.

3.3 Network topology processor

In the context of AC grids, different approaches such as the application of the intelligent methods or the integration of Phasor Measurement Units (PMU) for the purpose of topology processing have been investigated [104][105]. A centralized topology processor for a PMU-only state estimator is presented in [40]. An alternative method for topology processing using an expert system for detection of device malfunction at the distribution substations based on local state estimation is proposed and evaluated in [80]. A method for the identification of breaker statuses in power system state estimation is presented in [69]. In this method, additional pseudo measurements for each circuit breaker are also introduced to facilitate the identification process. This identification happens at a central level. Similarly, [70] presents a model for breaker status identification and power system topology estimation based on auto-associative neural networks.

Most of the previous works have emphasized processing the topology at central level (one-stage processor) which limits applicability of the topology processor for carrying out local and distributed control functions. Considering more flexibility in power system automation and communication due to the recent evolutions in computerized substation automation system and moving toward more distributed solutions for power system operation, the study of different methods than conventional one-stage solution for processing the grid topology is necessary. Therefore, in paper [104] a two-level architecture has been proposed for a linear state estimator. This paper has shown that the two-level processing removes the bad data and topology errors, which are major problems today, at the substation level and therefore, resulting in a more accurate two-level state estimator. This work has described a new substation level calculations, called the substation level state estimator or zero impedance state estimator, that pre-filters all the real-time data at that substation. Furthermore, the paper focused on the mathematical algorithms for each level of state estimation. However, it just assumed that the substation level network topology is available for the estimation application without any further comment on how to calculate or process it.

Looking at possible operational strategies in HVDC grids, two requirements must be taken into consideration for design of the topology processor. First, the topology processor needs to function when coordination of converters is shared between connecting TSOs (i.e. distributed strategy). Second, if one TSO coordinates the grid centrally, a back-up distributed coordination plan can be considered to take over the responsibility in case of central failure. This back-up distributed processor must be able to fulfill time requirements of grid coordination functions such as power injection without any additional reformation of data exchange or processing. Therefore, paper 5 studied a two-stage network topology processor that uses either centralized or distributed method to identify grid connectivity. The proposed two-stage topology processor examines the DC substation topology in the first stage based on an automated graph-based algorithm. Then, the second stage determines the grid level connectivity including islands detection. Furthermore, as main contribution to related works, it formulated and presented a distributed methods for grid connectivity
identification in the second stage. The performance of the distributed grid identification has been tested to check if it can be used for distributed control application.
Chapter 4

Research Results and Discussions

This chapter presents the outcome and contribution of the research by summarizing the results of related papers for each individual objective.

4.1 Investigation of advanced control applications for HVDC grids operation

The first aim of the thesis is to investigate control applications that are needed for HVDC grids supervisory management. Furthermore, the requirements that should be considered to design of such control applications have been presented. In literature, different types of control functions for the HVDC supervisory controller have already been studied such as secondary control of DC voltage, AC/DC combined power flow and state estimation [21, 34, 45]. Taking into account the literature and the possible needs for control and operation of HVDC grids, three types of control functions have been determined in this thesis to be studied namely, coordination of power injection, selection of DC voltage controlling station (DC slack bus) and finally network topology processor. Among these three functions, selection of DC voltage controlling station is a new function that is missing in the literature. Therefore has been considered in this thesis. The idea of having coordination of power injection and network topology processor has been presented in the literature and then studied from different perspective. However in this thesis these functions are presented and formulated based on different considerations which are provided in following sections.

4.1.1 Coordination of power injection

The first control application is "coordination of power injection" in HVDC grid. The difference between the proposed control function and the combined AC/DC optimal power flow in literature such as [25,26,41] is in their objective functions, the boundary of the system and the rate of calculation (how often the control applications needs to be carried out). In paper 1, the coordination of power injection in HVDC grids has been first formulated
as a non-linear constrained optimization problem for the centralized architecture. This optimization problem aims to tune the power injection set-point of converters to follow the schedules set by the connecting AC TSOs while minimizing the operational costs of HVDC grid. For this, the divergence of the converter power injection from the connected TSOs’ desired power schedule has been considered as a penalty to be minimized. This means working as close as possible to the desired value, \(P_i^{\text{des}}\). The desired value is the set-point normally assigned each 15-minutes by the AC TSOs. The same penalty has been considered for the DC voltage. This term helps converters to avoid large deviations in DC voltage and approach the limit after each disturbance. In addition, the power loss of the DC lines and converter loss have been also considered in this formulation (see equation 4.1).

\[
f = \sum_{i=1}^{N_{\text{conv}}} C_{p,i}(P_i^{\text{dc}} - P_i^{\text{dc}_{\text{des}}})^2 + C_{u,i}(U_i^{\text{dc}} - U_i^{\text{dc}_{\text{des}}})^2 + \sum_{i=1}^{N_{\text{conv}}} P_{\text{loss},i} + \sum_{i=1}^{N_{\text{line}}} P_i
\]

(4.1)

where,

- \(P_i^{\text{dc}_{\text{des}}}\) is the desired DC power injection at the converter \(i\) defined by the corresponding TSO in each balancing period (e.g. 15 minutes),
- \(P_i^{\text{dc}}\) is the optimal power injection set-point to be calculated for converter \(i\),
- \(C_{p,i}\) is the cost for the deviation from each TSO’s power injection plan at converter \(i\),
- \(C_{u,i}\) the penalty for the DC voltage deviation at converter \(i\),
- \(P_{\text{loss},i}\) is the loss at converter \(i\)
- \(N_{\text{conv}}\) is the number of converters,
- \(N_{\text{line}}\) is the number of lines,
- \(P_i\) is power flow on the line \(i\).

This formulation also includes equality constraints for DC power at each injection or consumption node (converter node) as well as inequality constraints on power and DC voltage limitations of converters and DC lines. Since the boundary of the problem involves just the HVDC grid and its controllable converters, this control application is capable to be run much faster that overall AC/DC combined power flow which considers the entire power system. Therefore this control function enables the converters to update the set-points more frequently in a system with fluctuating power and voltage profiles such as HVDC grids with large wind farms. Paper 1 studied the benefit of faster updating frequency i.e. within the 15-minutes intervals using this HVDC grid control application. For this purpose, the optimal power injection set-points have been calculated in different intervals from every 1-min interval to every 15-min interval and all the variation of power in the HVDC grid between the updating of set-points has been assumed to be taken by DC voltage droop control. As shown in Fig 4.1 for the specific system and wind data, the 1-minute-based power coordination can decrease the total cost function (equation 4.1) by around 16% compared to having the DC voltage control taking over the wind power mismatches.
4.1.2 DC slack bus selection

Selection of DC slack bus is always a matter of optimization which takes time and requires careful consideration. This selection can be significant after loss of the slack converter in an HVDC grid or in an islanding scenarios. Considering this requirement, it is important to find algorithms that examine the validity of the stations to take the role of DC slack bus. Paper 2 proposed that this control application uses a real-time quantitative evaluation of HVDC converters’ in an HVDC grid to rank and select the suitable DC slack converter. Various parameters could be considered for quantitative evaluation of a converter. Since the final aim of the thesis is to focus on the distributed solution, the parameters that required local information and measurements are of interest. On-line power margin of the converter and the strength of connected AC grid (i.e. short circuit capacity) are two examples of such parameters. Paper 2 highlighted the importance of these two parameters by a set of scenarios for the CIGRE B4 DC grid model available in [99]. For power margin, it is assumed that the current slack converter does not have enough margin to compensate the mismatch. This phenomena drops the DC voltage profile in the entire HVDC grid. The decrease in DC voltage corresponds to an increase in the current to maintain the same amount of power exchange. Higher current profile leads to increase in transmission losses. For short circuit capacity, different SCC have been assumed for the AC grid connected to the DC slack bus. The result shows that the lower SCC value of the AC grid connected to the slack converter, the higher is the disturbance in the AC voltage.

Given the importance of these parameters to evaluate the converter’s capability, a systematic ranking function based of these parameters have been proposed in paper 2 and examined through a scenario. In this scenario, converter Cb-A1 has high SCC and relatively high ranking value and therefore works as slack bus. This is the case until $t = 20s$ when an AC line trips. This trip reduces the SCC of the AC grid connected to Cb-A1. After the change in SCC of one AC grid, the evaluation of converters based on new SCC and power margin is carried out at $t = 25s$ that is detailed in Table 4.1. The ranking table shows that Cb-B1 is the best choice to act as a DC slack bus in the new situation while the reduction in SCC have caused the ranking of Cb-A1 to go to $3^{rd}$ place. Two cases have been considered: Case 1) Cb-A1 still continues to work as DC slack bus, although it is low...
ranked and CASE 2) Cb-B1 is selected as DC slack bus based on ranking table. To check these two cases, at $t = 30s$, the active power set-point of Cb-B2 is increased. In Case 1 where Cb-A1 still continues to work as slack bus, the DC voltage profile in entire HVDC grid is reduced since the power margin in Cb-A1 is low and it hits the limit. On the other hand, as shown in Fig. 4.3, the DC voltage profile is improved in the second case when Cb-B1 is chosen as the slack converter based on the ranking table.

Table 4.1: Slack Converter Ranking at $t = 25s$

<table>
<thead>
<tr>
<th>HVDC Station</th>
<th>Estimated SCC (GVA)</th>
<th>Power Margin (MW)</th>
<th>Evaluation Value</th>
<th>Slack converter Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cb-A1</td>
<td>13.15</td>
<td>316.32</td>
<td>0.0995</td>
<td>3</td>
</tr>
<tr>
<td>Cb-B1</td>
<td>14.89</td>
<td>878.16</td>
<td>0.2182</td>
<td>1</td>
</tr>
<tr>
<td>Cb-B2</td>
<td>9.06</td>
<td>699.36</td>
<td>0.1057</td>
<td>2</td>
</tr>
</tbody>
</table>

Regarding the effect on the AC voltage, since SCC is low in Cb-A1, if it continues to work as a slack bus (i.e. case 1), the change in the operating point causes the larger disturbance in the connected AC grid compared to the case 2. Consequently, as shown in Fig. 4.4.a, the AC voltage response of Cb-A1 is better in case 1 compared to case 2. The same applies for AC voltage response at Cb-B1 as shown in Fig. 4.4.b. The results in paper 2 show that the usage of this control application (i.e. selection of the slack station) improve AC system response and DC voltage drops during disturbances.
4.1.2.1 Network topology processor

The network processor uses the real-time circuit breaker status within the substation to determine the system level topology. The role of the topology processor becomes more critical in case of islanding where the converters in each island should be recognized as soon as possible and in some cases, be tuned in terms of their control modes (e.g. selecting DC slack bus). Most of the previous works carried out for AC grid (e.g. [40, 104, 105]), have emphasized processing the topology at central level (one-stage processor) which limits applicability of the topology processor for carrying out local and distributed control functions. The proposed two-stage topology processor in paper 5 examines the DC substation topology in the first stage based on an automated graph-based algorithm. Then, the second stage determines the grid level connectivity including islanding detection. The results show that the two-stage topology processor benefits from: 1) a faster process compared to one-stage method since each calculation at the substation is simpler and it is distributed in parallel, 2) the second stage (central level) is less complicated and needs smaller storage capacity as it has to manage data with reduced dimensions, and finally 3) the two-stage architecture makes it possible to use the information processed at the first stage for both distributed and central coordination. Therefore, the distributed coordination can simply be used as a
back-up plan for the central coordination without any further modification.

4.2 Distributed solution for control applications in an HVDC grid

The previous section emphasized the need of advanced control applications as part of an HVDC grid supervisory management system. Those control functions have been first designed and tested for the centralized architecture. However, the main contribution of the thesis is to investigate the feasibility of distributed solutions for the determined control applications, so they can be decomposed and implemented for distributed operational structure presented in Fig. 1.3.b. In addition, this solution could be also used in the central structure (Fig. 1.3.a) as a complementary back-up if the grid central coordinator fails.

4.2.1 Distributed coordination of power injection

In paper 1, the first control application (i.e. coordination of power injection) has been decomposed for the distributed implementation using Auxiliary Problem Principle (APP). To do so, as shown in Fig.4.5, a fictional border bus has been defined in the middle of the DC line that connects the converter $i$ in area $A$ to converter $j$ in area $B$. This border bus added state variables of DC power ($P_{dc}^{ij}$) and DC voltage ($U_{dc}^{ij}$) to the optimization problem. These two variables are shared variables between areas $A$ and $B$. Given the sub-problem in area $A$, it consists of the local variables of DC voltage ($U_{dc}^{i}$) and DC power injection ($P_{dc}^{i}$) for the local converter and the shared variables of $P_{dc}^{ij,A}$ and $U_{dc}^{ij,A}$ for border bus in the area. The new objective function and the related constraints have been formulated based on these variables in each subproblem and an iterative method has been used to solve the optimization problem. The detailed formulation is presented in paper 1.
The result of paper 1 shows that the convergence rate of distributed solution based on APP for coordination power injection in a 5-terminal HVDC grid (shown in Fig.4.5) is around 240 iterations. Taking into account the average delay of few hundred milliseconds for the data exchange in each iteration, update frequencies of once per minute that has been suggested in previous section might give problems, but slower update rate can be managed using this distributed algorithm. In paper 4, the boundary of the problem has been extended by considering the N-1 security constraints and uncertainty of wind production in the optimization problem. Besides, a linear approximation has been used to deal with non-linearity of constraints in each subproblem. In addition, to improve the performance of distributed coordination, a modified version of ADMM has been proposed instead of APP to solve the problem.

To evaluate the performance of proposed distributed coordination in paper 4, three different values have been set for the convergence tolerance. Then, the result of these three distributed cases have been compared with the centralized solution. The converters’ set-points and the corresponding objective function calculated in the centralized method have been presented in Table 4.2. For distributed implementation, at first, a relaxed tolerance of $\epsilon = 10^{-5}$ has been set. The result shows that the algorithm converges in 14 iterations. But the deviation from the optimal solution (objective function) is about 2.9%. By tightening the tolerance to $\epsilon = 10^{-8}$, as expected, the deviation from optimal objective function reduces to 0.06% which is a very acceptable error level. However, this accuracy comes with the expense of increase in iterations. Given the maximum communication delay of 50 ms between HVDC stations [109], it takes around 5 seconds for the algorithm to exchange data to converge. However, the computation time of solving subproblems in each iteration should also be added to the total time. This computation time can vary based on the power of local solvers. In this simulation, on average, it takes around 0.23 second to solve the local problem. Therefore, for the third case with the tight tolerance of $\epsilon = 10^{-8}$, the whole distributed coordination process take less than 30 seconds which satisfies the assumption of 1-minute requirement for updating the set-points.

<table>
<thead>
<tr>
<th>node</th>
<th>central $P_{\text{inj}}$</th>
<th>distributed $P_{\text{inj}}$</th>
<th>$\epsilon = 10^{-5}$</th>
<th>$\epsilon = 10^{-6}$</th>
<th>$\epsilon = 10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{\text{inj}}$</td>
<td>error</td>
<td>$P_{\text{inj}}$</td>
<td>error</td>
<td>$P_{\text{inj}}$</td>
</tr>
<tr>
<td>1</td>
<td>-0.4805</td>
<td>-0.4805</td>
<td>0.0008</td>
<td>-0.4805</td>
<td>-0.4805</td>
</tr>
<tr>
<td>2</td>
<td>-0.5633</td>
<td>-0.5636</td>
<td>0.0014</td>
<td>-0.5633</td>
<td>-0.5633</td>
</tr>
<tr>
<td>3</td>
<td>0.7170</td>
<td>0.7161</td>
<td>0.0010</td>
<td>0.7170</td>
<td>0.7170</td>
</tr>
<tr>
<td>4</td>
<td>-0.3994</td>
<td>-0.3988</td>
<td>0.0006</td>
<td>-0.3994</td>
<td>-0.3994</td>
</tr>
<tr>
<td>5</td>
<td>0.7560</td>
<td>0.7565</td>
<td>0.0005</td>
<td>0.7560</td>
<td>0.7560</td>
</tr>
<tr>
<td>iter.</td>
<td>--</td>
<td>14</td>
<td>34</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>cost</td>
<td>1.2878</td>
<td>1.3254</td>
<td>1.2895</td>
<td>1.2886</td>
<td></td>
</tr>
</tbody>
</table>
4.2.2 Distributed parameter estimation for DC slack bus selection

As mentioned earlier, a quantitative ranking framework has been proposed to evaluate the credibility of converters to take over the DC slack bus responsibility. To be able to select the slack bus in a distributed manner, each converter should be able to calculate its quantitative evaluation value based on local information. Then, with a light consensus protocols, they can agree on the selected converter. To obtain the quantitative ranking value, each converter needs to calculate two parameters (i.e. power margin and short circuit capacity). Given easy access to the first parameter i.e. power margin, the performance of the distributed implementation of slack bus selection in terms of accuracy, time and complexity would be very dependent on the estimation of SCC. Therefore, in paper 3, it is shown that the recursive least square algorithm can be very efficiently used for online estimation of SCC of AC grids from the PCC. As mentioned, to estimate two different parameters of the grid i.e. equivalent voltage and impedance for short circuit capacity calculation, RLS algorithm needs minimum two operating points to form the algebraic equations. Both active and passive methods can be used to introduce the second operating point to the estimation algorithm. Natural load changes in AC grid and change in DC side due to droop characteristics of the controller are two examples of passive methods that are presented in paper 3. A scenario has been considered to show the performance of algorithm in case of introducing the second operating point with passive methods. To do so, a point-to-point HVDC system shown in Fig.4.6 is considered.

![Figure 4.6: AC and DC system model.](image)

The SCC of the AC grid connected to Cb-A1 is changed from 12.82 GVA to 10.04 GVA by tripping a transmission line at \( t = 20s \). This change in SCC at \( t = 20s \) second is detected by the estimation algorithm and it resets the algorithm. The change in the operating point of Cb-A1 due to the change in active power schedule at Cb-B1 provides the second operating point for the algorithm at \( t = 30s \). Fig. 4.7 shows that the estimation algorithm in station...
Cb-A1 converges with adequate accuracy, immediately after the introduction of the second operating point by passive droop response. In this case, the latency in parameter estimation is dependent on when this natural response (either load change or droop response) occurs.

![Figure 4.7: Estimated short circuit capacity using the droop response as the second operating point.](image)

However, these passive methods might not be available in all circumstances. Therefore, to have faster estimation, three active approaches have been introduced in paper 2 and 3 to assure the availability of the second operating point for the estimation algorithm. In active approach, the active or reactive power set-points of the HVDC station or both of them can be changed manually by a small percent. Fig. 4.8 compares the estimated SCC for different types of changes in the set-points. The comparison is limited to a 3% change in the set-points. Note that paper 3 elaborates the choice of 3%. Fig. 4.8 shows that all three cases have similar ranges of accuracy. In all cases, the algorithm converges to an acceptable value in a few seconds. Taking into account that minimal disturbances to the grid are desired, the change in reactive power set-point can be recommended.

In addition to the choice of operating points, the performance of estimation algorithm is dependent on other parameters such as execution time, filter time constant, noise in measurements, X/R ratio of the AC grid and etc. In paper 3, a comprehensive sensitivity analysis has also been carried out to assess the impact of these parameters and operational conditions on the performance of estimation algorithm. However, two parameters of execution time as well as filter time constants have been shown to have critical impact on the performance and convergence of RLS algorithm.

To show the effect of algorithm’s execution time, it is assumed that the power system model is running with a sample time of 7.407μs, whereas the controllers are operated with a sample time of 74.07μs and the RLS estimation algorithm can be run with the same sample time as the controllers (1x) or slower. The results of the estimated short circuit capacity for the different execution times are shown in Fig. 4.9. The speed of "2x" that corresponds to a sample time of 148.14μs (2 * 74.07μs) has the best accuracy. The result also suggests that the sample time of 222.21μs ("3x") has enough precision for the practical implementation.
which also does not enforce a high speed requirement.

Regarding the time constants of measurements’ filter, result in Fig. 4.10 shows that the
algorithm diverges for both small and large time constants. The algorithm is accurate for
the range of 20ms to 50ms. There is no major difference in the results of estimated SCC
within this range of time constants.

To summarize, comprehensive studies in paper 2 and 3 show that the RLS algorithm
can provide a fair estimation of SCC in range of a few seconds, given the algorithm is tuned
properly in terms of its operational parameters and conditions.

4.2.3 Distributed identification of grid topology

One of the prerequisites for distributed coordination of converters is the knowledge of neighboring stations’ connectivity. One motivation to choose the two-stage network processor
is the possibility to extend the approach for distributed implementation. Since the first level of substation connectivity processing takes place locally, the neighboring substations have the opportunity to ask for the processed information (e.g. in the form of $S_m$ matrix presented in paper 5) from each substation for further grid level topology processing. Then, the local adjacency matrix $A$ can be updated using $S_m$ matrices received from all neighbors. This connectivity to other neighboring stations is the information needed for the distributed power injection coordination during normal operation presented in paper 1 and 4. However, for islanding events, additional information must be provided to the control application regarding which converters are within the island. A distributed algorithm to detect the connectivity during islanding scenarios has been developed in paper 5. This algorithm checks the connectivity of each node to a specific node called source node by forming linear equations. Then, it uses successive-over-relaxation method to solve the linear problem.

The performance of the distributed two-stage architecture is compared with the conventional centralized architecture and central two-stage architecture in terms of computational efforts. For conventional centralized architecture, it is assumed that all breaker status are sent to a SCADA system and there the topology processor is detected. For central two-stage architecture, it is assumed that the first-stage is carried the similar to the proposed method, but the second-stage is performed centrally in one entity instead of our distributed proposal. This comparison has been carried out for an islanding scenario and a Core-i5 machine with 2.30 GHz CPU and 8.00 GB memory has been used. To have a fair estimation of the process time, this scenario has been run 100 times and the results have been averaged.

To compare different architectures, the worst case (i.e. longest substation processing time or slowest substation) has been chosen for the substation topology detection. In the two-stage architecture, for the 5-terminal grid model in paper 4, the longest local processing is done by substation 4 with 9 breaker. This design time of 42.26 s and operation time of 0.2845 s are presented in this table. For the distributed coordination, the islanding detection happens at the substation level. As shown in Table 4.3 each islanding detection algorithm takes 0.00057 s at the local level. As mentioned before, to realize the connectivity to other nodes, a parallel detection algorithm should be run based on number of nodes in the
grid. Given the 5-terminal HVDC grid model, each node needs to run 5 sets of algorithm in parallel, 4 sets for checking the connectivity to other nodes and one set of algorithm to act as source node to others. Therefore, the total time of the islanding detection in the distributed coordination is calculated by multiplying the number of iterations for each set of algorithm to converge, number of parallel algorithm and execution time of each algorithm (i.e. total time = 5 × 5 × 0.00057 s). This results in the execution time of 0.01425 s for only islanding detection. However, in the central two-stage processor, the grid topology is processed in 0.0063 s and in the conventional centralized architecture, the grid topology detection takes 151.57 s and 0.4055 s, respectively. There is no substation processing time since all the breaker statuses are sent to the central processor.

Table 4.3: Comparison of different topology processing architectures.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Substation topology</th>
<th>Grid topology</th>
<th>Total without delay</th>
<th>Total with delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Two-stage (central)</td>
<td>Design</td>
<td>42.26 s</td>
<td>42.26 s</td>
</tr>
<tr>
<td>Operation</td>
<td>Conventional</td>
<td>Operation</td>
<td>0.2845 s</td>
<td>0.2845 s</td>
</tr>
<tr>
<td>Islanding</td>
<td>Two-stage (distributed)</td>
<td>Islanding</td>
<td>–</td>
<td>0.0057 s</td>
</tr>
<tr>
<td>Design</td>
<td>–</td>
<td>Design</td>
<td>151.57 s</td>
<td>–</td>
</tr>
<tr>
<td>Operation</td>
<td>0.0063 s</td>
<td>Operation</td>
<td>0.4055 s</td>
<td>0.41425 s</td>
</tr>
<tr>
<td>Total</td>
<td>without delay</td>
<td>Total</td>
<td>0.290 s</td>
<td>0.2987 s</td>
</tr>
<tr>
<td>with delay</td>
<td>0.340 s</td>
<td>with delay</td>
<td>0.455 s</td>
<td>0.5485 s</td>
</tr>
</tbody>
</table>

The last two rows of Table 4.3 present the total processing time in all three architectures without considering communication delay and also with an identical scenario but considering communication delay. The total grid topology processing time is in the same range for the two-stage processor with either central or distributed coordination. Considering a communication delay of 50 ms, the distributed coordination requires longer processing time than the two other methods.

4.3 Benefit of real-time co-simulation platform

The distributed control of HVDC grid involves the interaction of physical power systems and distributed decision makers, which are basically computational/communication units. Therefore, such an interaction can be studied from a cyber-physical system perspective. To do so, as mentioned before, it requires development of a multi-domain co-simulation platform. In this thesis, the key considerations to develop the co-simulation platform have been: easy configuration and operating system compatibility, ability to interconnect with external third-party program/system, hardware-in-the-loop (HIL) capability, time resolution of simulation steps, time synchronization, level of detail of modelling, interoperability to import models and scalability.

The real-time co-simulation platform developed in this thesis is a general real-time architecture that can be rearranged for different studies from distribution grids control scenarios [10] to wide area control of transmission grid [12]. This platform includes real-
time power system simulator, real-time communication network simulator, applications, and software-based or real interfacing devices/measurement. The main key factor in the development of such real-time platform is accuracy and performance of the software-based models of the real devices and the implementation of industrial automation protocols such as synchronized phasor measurement units. For the scope of this thesis, the platform is configured to support the modelling of HVDC grid and its corresponding HVDC converter controllers and communication system (see Fig. 4.11). The detailed information of the components has been described in Paper 6.

![Real-time co-simulation platform configured for HVDC grid control studies.](image)

Figure 4.11: Real-time co-simulation platform configured for HVDC grid control studies.

The results in Paper 3 and 6 show that design, testing and implementation of distributed control applications for HVDC grids would significantly benefit from developing a proper co-simulation platform. As an example, in paper 6 the comparison of pure simulation versus real-time co-simulation implementations of a distributed power flow has been presented. The result shows that some dynamic of the real controller and errors in A/D conversion cannot be captured in the pure simulation. Similarly in paper 3, the performance of the

![Performance of short circuit capacity estimation algorithm in non real-time and real-time platforms.](image)

Figure 4.12: Performance of short circuit capacity estimation algorithm in non real-time and real-time platforms.
SCC estimation algorithm (to be used for DC slack selection) has been evaluated using a non-real-time environment (pure simulation) as well as the real-time co-simulation platform. The implementation in real-time co-simulation leads the estimation algorithm inside real industrial controller hardware faces the noises of measurement devices as well as the small delay in communication. The comparison of short circuit capacity calculated in simulation and co-simulation platforms shows that the estimation algorithm is able to provide accurate results (error less than 2%) even in presence of noise and harmonics (see Fig.4.12).
Chapter 5

Conclusion and Future Work

In this thesis, three functions are investigated to be deployed in HVDC supervisory system: coordination of power injection set-points in the presence of large wind farms, DC slack bus selection and two-stage network topology identification. Considering the coordination of power injection in HVDC supervisory brings the possibility of updating the operating point of HVDC converters more frequently (every 1-min) when the system is subjected to variation in wind production. Since the new operating points calculated by this function are forced to work as close as possible to the set-points set by overall AC/DC management system, the generation reserves in each AC area can be improved. To coordinate the power flow inside the HVDC grids, the control mode of converters especially the DC voltage controlling converter (DC slack bus) is of importance. The choice of DC slack converter can impact the voltage respond of both AC and DC system after a disturbance in the system. Furthermore, this selection procedure can be significant after loss of the slack converter in an HVDC grid. In this thesis, a close-to-real-time evaluation framework is developed to choose the appropriate DC slack bus in an HVDC grid. This online quantitative evaluation examines the strength of all AC grids connected to the converters (characterized by grid’s short circuit capacity) and post-contingency capacity margins of the converter. Both parameters are local information.

When it comes to implementation of supervisory control functions, this was coupled tightly to the arrangement of system operators i.e. if there is an individual HVDC operator (centralized) or tasks are shared among different entities e.g. AC operators (distributed). This arrangement of operators brings two considerations for the design of HVDC supervisory functions. First, the control functions need to work properly when the coordination of converters is shared between connecting TSOs (i.e. distributed structure). Second, if one operator coordinates the grid centrally, a back-up distributed coordination plan is determined to take over the responsibility in case of central failure.

Based on type of control functions, different algorithms can be considered to decompose and distribute the function. For coordination of power injection, the updating rate of 1-minute is considered as a requirement to evaluate the distributed solution. In this thesis, two different distributed algorithms based on alternating direction method of multipliers and auxiliary problem principle are used to solve coordination of power injection which satisfy the required updating rates. However, in DC slack bus selection, for distributed
implementation, the choice of parameters for online quantitative ranking is important. These parameters should be calculated based on local measurements if distributed decision making is desired. To estimate the short circuit capacity as one of the required parameters for selection of DC slack bus, the result of this thesis determines that the recursive least square algorithm can be very efficiently used. Besides, it is possible to intelligently use a naturally occurring droop response in HVDC grids as a local measurement/information for this estimation algorithm instead of active methods to introduce measurement points.

Regarding the identification of grid topology for control purposes, considering a two-stage network topology processor provides a faster process compared to one-stage method since each calculation at the substation is simpler and it is distributed in parallel. Besides, the second stage (central level) is less complicated and needs smaller storage capacity as it has to manage data with reduced dimensions. As main advantage, the two-stage architecture enables to use the information processed at the first stage for both distributed and central coordination. Therefore, the distributed coordination can simply be used as a back-up plan for the central coordination without any further modification.

Future work

There is more room to expand this research topic from different perspectives. Looking at OBJ 1 (i.e. to investigate advanced control functions), although there have been some studies on different control functions for HVDC supervisory control level, but still comprehensive studies on other functions can be carried out such as HVDC grid state estimation, ancillary support and droop setting design.

Regarding the implementation of control functions, this thesis focused on the solution for distributed operational structure. However, in future it might be the case that one of the connected AC areas’ operators take over the responsibility of HVDC grid. This scenario is also valid if an embedded HVDC grid in one AC area is of interest. This can impact the boundary and objective function of the power injection coordination problem.

One area that might need further studies is the selection of DC slack bus. First, this selection can be generalized for any type of converter that contribute in power sharing e.g. DC voltage droop controllers. In that case the problem will be the adaptive tuning of control parameters such as droop coefficient. In addition, other parameters can be considered for the evaluation of slack bus such as generation reserve of AC areas. On the SCC estimation, the equivalent grid estimation can be more challenging when the AC grid includes large amount of converter-based generating units such as PV and wind plants.
Bibliography


Part II
Papers 1 to 6
Paper 1
Study of Centralized and Distributed Coordination of Power Injection in Multi-TSO HVDC Grid with Large Off-shore Wind Integration
Paper 2
Selection of DC Voltage Controlling Station in an HVDC Grid
Paper 3
Real-Time Estimation of Grid Short Circuit Capacity for HVDC Control Application
Paper 4
Distributed Security-Constrained Secondary Control of HVDC grids in the Presence of Wind Uncertainty
Paper 5
Analysis of Centralized versus Distributed Two-stage Network Topology Processor for HVDC Grid
Paper 6
Implementation of agent-based power flow coordination in AC/DC grids using co-simulation platform