Cyber Physical Approach to HVDC Grid Control

Lars Nordström and Davood Babazadeh

Abstract. This chapter presents a cyber-physical approach to design of HVDC control system architectures and evolving HVDC grid operation and control modes. In addition, the chapter describes the communication system architectures needed for centralized and distributed operation and control of HVDC grids. Modeling and analysis methods suitable to analyze such systems using graph theoretic concepts, and also the design of distributed control systems utilizing a Multi-Agent approach and its dependence on the information graph theory. The chapter is concluded with a description of an application for distributed control of DC grids utilizing the concepts introduced. The application is presented both with regards to comparison with other design choices and analysis of performance and robustness of the algorithm versus communication metrics.

1 Multi Terminal HVDC and HVDC Grids

This section provides background and overview to the development towards High Voltage DC (HVDC) grids. The section is started with an introduction to some of the driving forces behind the development. Thereafter two key technologies for HVDC grids – the Voltage Source Converter and the DC breaker are presented in some detail. The section is concluded with a discussion on the type challenges that appear for DC system operation in various configurations.

1.1 HVDC Grid Rationale

In the recent power system expansion driven by growing energy demand, more attentions are being put toward integration of large-scale renewable resources.

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This is tangible by observing the intention of the European Union in producing 20 % of its electric power needs through renewable resources by 2020 [1]. The benefits of integration of renewable resource such as wind or solar have been justified through many researches and to some extent in real-world projects. 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. Furthermore, the expansion of the grid involves problematic legislative rights-of-way efforts limiting the speed of expansion. Therefore, recently there is a considerable attention drawn to application of HVDC transmission grids on top of, or in complement to, existing AC power systems as a solution to these limitations on integration of renewable resources. Potential benefits of such an HVDC grid includes the possibility to access remote energy sources thereby increasing renewable penetration, improve grid security and decrease congestion in the system [2].

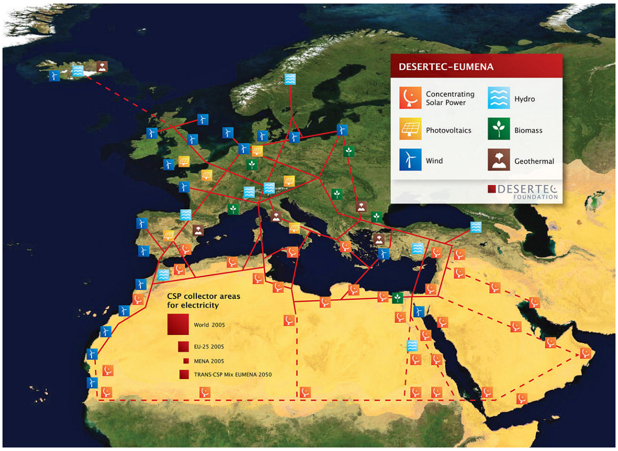

Fig. 1 Schematic of HVDC connections in DESERTEC project

In this regard, there have been several proposals and projects to study the feasibility of such HVDC grids in the European power system from market, technical, as well as political perspectives. For example, the conceptual study of a *Supergrid* proposes a HVDC network connecting offshore and onshore Supernodes that collect the remote renewable energy and transmit it to the existing power grid on land. On prime target application for the Supergrid is to integrate Europe's abundant offshore wind in the North Sea [2]. In parallel, another European project DESERTEC aims to develop a wide renewable energy integration plan to harness sustainable power from remote sites to load centers also see Fig. 1. Although this project covers all kind of renewable resources, but it emphasizes the sun-rich deserts with solar energy capabilities [3].

Besides these proposals, there have been similar projects planned and some of them partially installed. For example, the North-East Agra project in India aims to use series DC links that form a multi-terminal HVDC system to transfer power to loads. The North-East Agra links can transfer around 65000 MW hydro power resources scattered in a large area in the north of India to electrify around 90 million people. Once operational this system will be the world's first multi-terminal Ultra-HVDC link with four terminals [4].

1.2 HVDC Grid Technologies

In order to convert high voltage AC power to DC power, two well-known technologies are available, classical line commutated converter (LCC) and the voltage-source converter (VSC).

Line Commutated Converter (LCC) uses a semiconductor switch called thyristor to rectify AC current. Thyristors similar to diodes only conduct current when the AC voltage over them is positive. The difference however, is that thyristors need to be turned on, or fired, in order to begin conducting. 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.

Voltage Source Converter technology uses Insular Gate Bipolar Transistors (IGBT) instead of thyristors. The IGBT semiconductor can be controlled both with regards to being turned on or off. In VSC technology, the DC current on the DC link can be flowed 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 weaker grids which has low short-circuit level. In addition, in contrast to LCC, VSC has two degree of control which makes it capable to control the active power and reactive power separately. One challenge with IGBT based VSC is that they have less overload capability compared to LCC.

Regarding HVDC grids development, the VSC technology is due to its power flow flexibility the suitable solution to build meshed topology grids. On the other hand, in order to transfer higher power capacity in a series link topology (similar to North-East Agra project) LCC technology is more suitable. Since in this chapter, the core of the work refers to meshed HVDC grids, the following sections focus on introducing the VSC technology.

The implementation of meshed HVDC grids brings different challenges which the most important one is the need for DC breakers in the case of fault in the HVDC grid. In HVDC grids, the DC lines require to be equipped with DC breakers to de-energize the faulty line and keep the intact part of the DC grid in operation in order to increase the utilization factor of the whole system.

1.3 VSC Technologies

In contrast to LCC technology, the VSC has an additional degree of freedom to also control reactive power separate from the active power. This freedom comes from controlling the converter using the Pulse Width Modulation (PWM) technology. PWM lets the magnitude and phase of the voltage be controlled spontaneously which allows independent control of active and reactive power.

In 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. In this approach, the injected current vector is set to follow a reference current vector.

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 [5].

The benefits of vector control method compared to direct method makes it the common control scheme in VSC-HVDC systems. Therefore, a brief description of vector-based control architecture for VSC-HVDC is presented in this section.

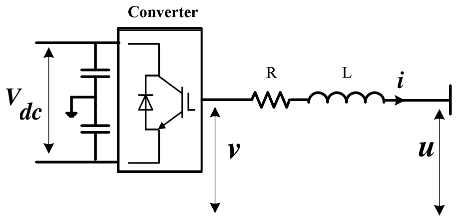

Fig. 2 Basic schematic of VSC

Fig. 2 shows a typical schematic of a VSC station. R and L are the resistance and inductance of the converter AC side that include the transformer and phase reactor parameters. Based on the schematic, the equation of the AC side in *abc* coordinates can be written as:

$$v_{abc} - u_{abc} = L\frac{di_{abc}}{dt} + Ri_{abc} \tag{1}$$

Where V is the AC voltage of the converter, U is the AC voltage at the point of common coupling (PCC) which connects the station to the AC grid, and i is the current coming/going from/to AC grid. The equation (1) in *abc* coordinates can be transformed to *dq* coordinates presented in equation (2). In these coordinates, both decoupled i_d and i_q currents can be controlled separately by Inner Current Control.

$$\begin{bmatrix} v_d - u_d \\ v_q - u_q \end{bmatrix} = \begin{bmatrix} R & -\omega L \\ \omega L & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (2)$$

The VSC control system includes an inner current controller which helps to control the current in *dq reference frame* and therefore leads to the decoupled control of active and reactive power in the converter. The complete schematic of an inner current controller is shown in Fig. 3. The inner controller follows the reference orders i.e. i_d^* and i_q^* that are set by outer controller.

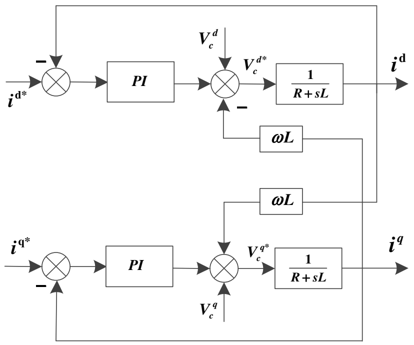

Fig. 3 Block diagram of the complete inner controller

The outer controller provides the inner controller with the reference current values in dq coordinate (i^{d*} and i^{q*}). The outer controller is able to control active power or DC voltage on DC side by controlling i^d (The injected active power in *dq* coordinates can be written as $P = V_s^q i^d$). The reactive power or AC voltage on AC side can be controlled by controlling i^q (if the voltage is aligned with the q-axis, the reactive power can be written as $Q = V_s^q i^q$). Due to the simplicity of PI controllers, it is normally applied in the outer controller (see Fig. 4).

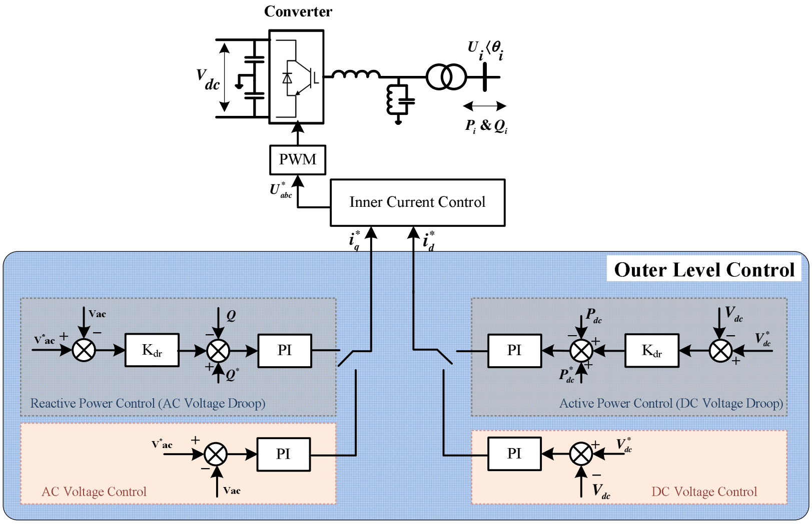

Fig. 4 Block diagram of the complete control system

As mentioned above, DC voltage is one of the parameters in the DC grid operation that can be controlled and therefor helps the power flow control in the DC side. Several control approaches such as Master-Slave, Voltage Margin and Droop have been proposed in literature [7][8][9]. These methods are described in the coming sections.

1.4 HVDC Grid Considerations

As shown above, the overlaid HVDC grid appears to be a promising solution for new demands in expansion of the current power system. However there are still some challenges to be solved to let this vision come to reality. The configuration of the grid, the grid protection and the ancillary services of the HVDC grid are some of those issues. Inspired by these challenges, some researchers have stepped further to examine the extra functionality of the HVDC grid in form of ancillary services [10][11].

1.4.1. HVDC Grid Topologies

One of the key parameters that has vital impact on the architecture of control and protection systems is without doubt the topology of the HVDC network. Different terminologies have been used for the overlaid HVDC connections based on the configuration of the network. To set a base for the discussions in this chapter, we start with the introduction of different topologies for HVDC connections and then clarify the terms "HVDC Grid" and "Multi-Terminal DC (MT-DC)".

The topology of the HVDC network has an indisputable correlation with the reliability of the system and also cost of the total development. This issue becomes even more important as the architecture of the control and protection system and the complete cyber physical system is fully dependent on this topology.

The first choice of topology for a grid is the point-to-point topology (PP) which comprises several point to point HVDC connections. This topology makes it possible to use just AC breakers in the case of failure in the DC line. On the other hand such a topology cannot fulfill the single failure criterion, since losing one link removes the whole connected generation. In a star topology (ST), a central star node connects all the nodes together. The dependence on the central node and reliability of this configuration is one of its drawbacks. Any fault at the central node can damage the whole DC system [12]. The general ring (GR) topology forms a ring with the lines connected to all the nodes. Lines must be designed for maximum capacities since they are needed to transfer the whole power of the system when the ring is opened. In this case, opening two DC circuit breakers placed on the end of a line can isolate a DC fault. Fast communication is however required to coordinate DC breakers to de-energize just the faulted line and keep the rest of the DC system up running.

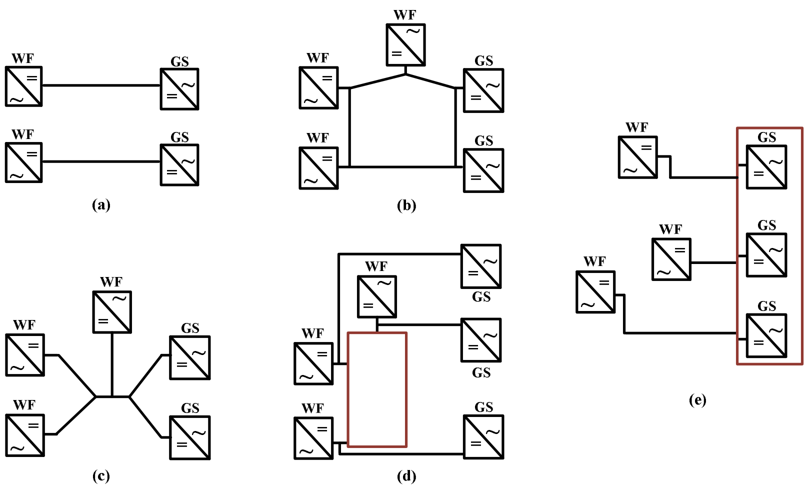

Fig. 5 HVDC grid topologies for off-shore integration (a) point to point topology, (b) general ring topology, (c) star topology, (d) wind ring topology, (e) substation ring topology

Another topology called wind farms ring (WR) provides an opportunity to minimize the costs by decreasing the number of breakers on the DC side. In this topology, there is a ring shaped grid connecting wind farms to each other [12]. Besides, each wind farm is connected separately to the AC grid. In this configuration, breakers are located on the links which connect ring DC grid to farms. This configuration enables the system to control the power flow between production and AC area in a more flexible manner. This topology is one of the strong candidates to be considered for future DC grid connected to offshore plants. Still fast communications is a requirement for this topology in order to coordinate the DC breakers in fault situations. Similar to this configuration, a ring can be considered for the AC side substations. In a substations ring topology (SSR), the wind farm converter must be isolated at fault instead of the AC side converter which is the case in wind ring topology. Therefore communication is still a considerable issue in this topology.

Considering all types of abovementioned topologies, the term MTDC is used for those kinds of the topologies that connect a number of converter stations in radial or parallel manner such as star topology or PP topology. This means there is no mesh inside such topology. The term “HVDC Grid” distinguishes the meshed network architecture from rest of the topologies such as WR or SSR.

1.4.2 Protection of HVDC Grids

One of the time-sensitive constraints in the domain of DC grid is the protection system for fault conditions which can cause many challenges in terms of economic and technical aspects of the DC grids developments. In DC grids, short circuit faults either line to ground or line to line leads to overcurrent faults. DC over voltage faults can occur due to open circuit in the grid or loss of a converter.

Converse to conventional HVDC which do not experience a large overcurrent during the faults due to its large DC smoothing reactance, the discharge of 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. A reliable and fast protection scheme is one the significant parameters in the reliability of the meshed DC grid.

The protection schemes proposed for DC faults e.g. [13][14] have addressed algorithms that do not use DC breakers. In [13], the method called handshaking method proposed which blocks all the HVDC stations in the fault condition and AC breaker is used to clear it. In [14], a method called a diode clamping method is proposed for small-scale system in which DC circuit breakers are not economically necessary. While in all those schemes, using the AC breakers causes the whole DC system to be de-energized for a moment, DC breakers with a fast clearing time can be used to disconnect just the faulty part and keep the intact parts of the DC grid in operation which increases the availability of the whole system. Innovative protection schemes that consider the topology of the grid and circuit breakers must be developed. These schemes will in turn have an impact on the architecture of the architecture of the communication network.

1.4.3 HVDC Grid Ancillary Services

Besides the transmission of active power from generation plants to load centers in normal operation, the 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 includes frequency support, voltage support and rotor angle stability in the form of avoiding loss of synchronism between generators or damping of electro-mechanical oscillations. In this section, a summary of such ancillary services is given.

Frequency Control

The change in the balance between loads and generations in an AC system leads to deviation in the frequency of the system. Such a deviation can be an indication to take control actions. This control action includes increasing or decreasing power production on the generation side or shedding loads on the demand side. Considering hybrid AC/DC grid i.e. including meshed DC grid on top of the AC grid, several studies such as [11] have suggested to take this possibility of the power injection control between DC/AC areas to control the frequency of the AC areas. Therefore, in the case of frequency deviation in one AC area, the remaining connected AC areas contribute in supporting the frequency through the overlaid HVDC grid. This ancillary function can prompt new schemes in the design of control system in both primary and secondary frequency control actions.

Voltage Support

The support of voltage profile at the connecting nodes on the converter can be implemented by injecting reactive power to AC areas. The voltage deviation especially over-voltage situation during faults can be managed independently by reactive power injection. This support function relies on fast actions of local TSO (the TSO controls the AC area connected to that converter) to dispatch reactive power reserves [11][15].

Oscillation Damping

The interactions of rotating machines in the power system can create oscillation modes. One of the vital control actions in the operation of power system is to damp these oscillations. In the new power system structure, the integration of large wind farms can introduce the power oscillation between the rotors of synchronous machine which is the new source of instability. Several studies suggest suitable control methods for point to point HVDC links in order to increase rotor angle stability. Most of the proposed schemes for point to point links can also be used in the case of HVDC grids [11]. This ancillary service can therefore also be considered during the design of upper control level for HVDC grids.

2 Communication and Control for HVDC Grid Control

In this section the operational and control principles that can be used for HVDC grids are provided. The importance of communication infrastructure on some the control schemes are explained.

2.1 HVDC System Operation

The current HVDC grids which are in the planning phase, such as abovementioned ones i.e. the Swedish South-West link or Indian North-East Agra are being developed by a single transmission system operator (TSO). One of the key challenges to be solved for larger HVDC Grids is the interaction between interconnected TSOs and ownerships of the HVDC grid. In case of an overlaid HVDC grid connecting separate AC areas involving several TSOs, different architectures can be proposed for the operation of the HVDC grid. These include the independent and the integrated architecture [11]. In the independent architecture, the DC grid is operated by a separate TSO called the DC grid operator, while in the integrated architecture, one of the connected TSOs is responsible for the control of the HVDC grid. In both architectures, the optimal power flow (OPF) must be calculated in order to run the system in the most optimal situation. The difference in the two architectures in the terms of the power flow calculation is in the required information, boundary of the system, and also objective (cost) function.

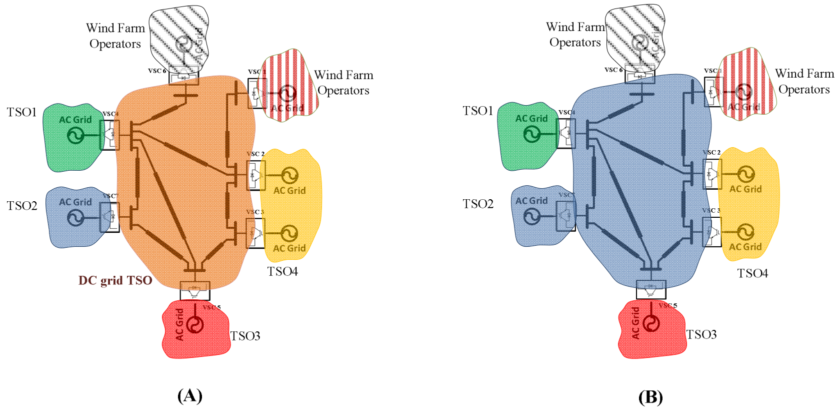

Fig. 6 Operational Architecture of HVDC grids, (A) Independent DC TSO (B) Integrated TSO

Independent Operation

As it is shown in Fig. 6, an independent TSO can operate the DC grid which lies between different AC areas. The DC grid TSO must follow the connection rules and policies set by connected AC TSO while tries to increase its operational benefits [11]. The functions such as optimal power flow, primary/ secondary frequency control and oscillation damping should be defined and implemented by this TSO. Based on the choice of design, these functions can be implemented in centralized or distributed manners. For both designs, the DC TSO needs to have permission to access the corresponding information from other AC TSOs.

Integrated Operation

In the second architecture, one of the TSOs takes the responsibility of operating the HVDC grid. Implementation of some the functions such as optimal power flow or rotor angle stability-related services are simpler in this architecture. In this case, there should be clear policies and agreement on the sharing of benefits from the operation of HVDC grids. The centralized and distributed approaches are again two choices for the implementation of functions in this architecture.

2.2 Communication and Control

As mentioned in previous sections, the HVDC converters are able to control active power or DC voltage on the DC side. The ability of controlling these two parameter give rise to different types of control schemes to operate the HVDC grid in reliable and efficient ways. Based on the required information in each scheme, some of the methods need fast communication while others are dependent on just local information. Master-Slave, Voltage Margin and Droop are three well-known proposals for control of HVDC grid.

Master-Slave scheme
In this scheme, one terminal is responsible for controlling the DC voltage and other converters operate at constant active power mode. This single converter is also responsible for compensate any imbalance in the HVDC grid power flow. Therefore it should be designed for large power deficits as well. The drawback of this design is that the system can collapse if the grid loses this dedicated DC control converter.

Voltage Margin scheme
Similar to the Master-Slave scheme, the Voltage Margin method assigns one converter to be responsible to keep DC voltage of the grid at a desired level and the other converters operate as constant power converter. In the case of losing or reaching the limit in this converter, another converter takes over the responsibility and works as the slack bus in the grid. As shown in Fig. 7, at current operating point, terminal 1 works on constant power mode and terminal 2 controls the DC voltage [16].

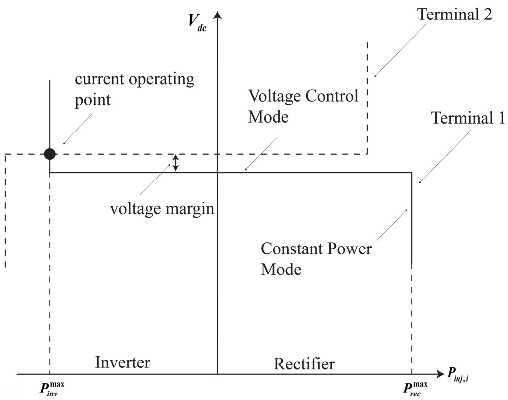

Fig. 7 Voltage Margin Scheme for two terminal system

Droop Scheme
Similar to frequency indication in the case of AC power mismatches, the DC voltage deviates if there is any imbalance in the power injection and extraction on the

DC side. This DC voltage deviation which is a local indication of power mismatch can be used as a control signal to increase or decrease the active power in converters. However there is a difference between frequency in AC and voltage in DC grid; the frequency deviation is almost similar in entire grid but the DC voltage deviation is different in each node. The DC voltage deviation has a direct relation with the topology of the grid.

Based on this characteristic of the DC grid, the Droop method lets some converters change their injected active power proportional to the local DC voltage deviation. The characteristics of converters for a two-terminal system are shown in Fig. 8 [16]. In this scheme, if there is a power loss in the system, the voltage drops in the entire DC grid, and the converters uses this value to inject more power to the grid or extract less power. This process is also valid for the reversed situation i.e. a power increase in the system. The problem with this method is the power sharing in the case of disturbances can not be distribute fairly. Besides, the droop parameter must be reassigned for the new operating point after each disturbance. This recalculation should be done by a centralized master controller. This controller/SCADA can be run by either the independent TSO or the integrated TSO.

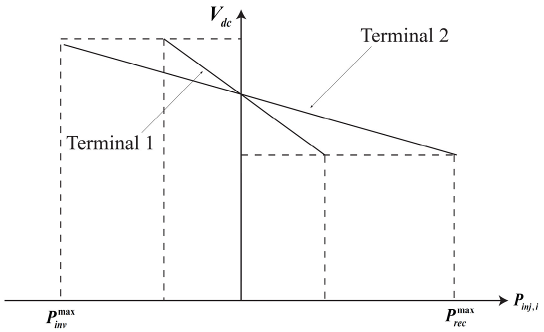

Fig. 8 Droop scheme for two terminal HVDC system

Power Flow Control

The power flow control in the HVDC grid can be carried out by calculating the proper set-point for the converter either on DC voltage control or on constant power control. This calculation needs to be implemented in either a centralized controller or distributed entities. In both cases, the calculator(s) needs the information from either the entire grid or the neighboring HVDC station. Power flow control based on type of implementation i.e. centralized or distributed requires different communication infrastructures. Note that in the case of droop control, the need of power flow controllers is more accentuated since the new stable point after disturbance does not guarantee fair and optimal power flow. Due to the slow dynamic of power flow control compared to voltage control, it can take up to seconds to determine the set-points of the converters.

Need of reliable ICT system

Operation of HVDC grid connecting multi AC areas is a complicated process that required robust control strategies and reliable supporting systems. The ICT system as one of the important supporting systems plays an important role in some of the control and protection architectures [17]. Here, we summarize the functions and architectures that rely on these supporting systems and then in further section the significance of studying and modeling of such a Cyber-Physical System will be emphasized.

As we have seen, the protection system in some grid topologies such as Point to Point, Grid Ring or Station Ring requires fast communication links to isolate the faulty DC line and keep intact areas operational. When it comes to control schemes, Master-Slave is the method needing fast communication to send power set-points. In the case of Voltage Margin or even Droop control, the new parameters for the new operating points should be calculated either centralized or distributed and sent to converters as soon as possible. In some literature this is referred to as power flow control. This function still requires communication between the neighboring nodes in the case of distributed flow control or between nodes and SCADA in the case of centralized approach.

3 HVDC Grids as Cyber-Physical Systems

This section describes the modeling of agent-based control for HVDC grids from a Cyber-Physical System perspective. The term Cyber-physical system (CPS) 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 [20]. First we describe how the control of power flow in the HVDC grid can be carried out by assigning a set of agents for the HVDC converters to perform the local tasks aligned with the global goals. The characteristic of this cyber physical system is thereafter described. Finally we describe the co-simulation testbed used to evaluate the multi-agent control scheme.

There are several research works that study the CPS concept from different perspectives such as design techniques or application of CPS to design power systems [21]. A cyber physical system model that could be scheduled and controlled to achieve the desired reference values and minimizing the power consumption of the given system has been proposed in [22]. The integration of ICT supporting system with traditional power system is more noticeable nowadays by implementation of new technologies like PMU-based monitoring systems. Such an integration of cyber elements to the operation and control of the power grid can increase the stability of the system. Modeling the power system as physical system interacting with such cyber devices has been further discussed in [23][24][25].

3.1 HVDC Control as a Cyber-Physical System

Voltage Droop and Voltage Margin are two approaches for control of DC voltage that have been described above. In both methods, a disturbance will shift the operating point of converters and as a result the power flow in both AC grid and DC grid will change. Such a new operating point cannot guarantee fair distribution of power in the grid. Therefore there can is a need of centralized or distributed coordinator(s) to allocate the power sharing in the HVDC grid. Since the converters in HVDC grid are dynamic and must coordinate locally or globally for certain control functions such as power sharing, the problem can be formulated in the context of Multi-Agent System (MAS) control. MAS contain a number of controllers called agents interacting with dynamic units. These agents are set to reach global goals. This concept is applicable in many areas such as formation flights, sensor networks, energy networks and distributed computation.

Such agent-based 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. Studying such integrated systems of systems requires comprehensive knowledge in different domains such as software engineering, communication and networking, control theory and also electronic design.

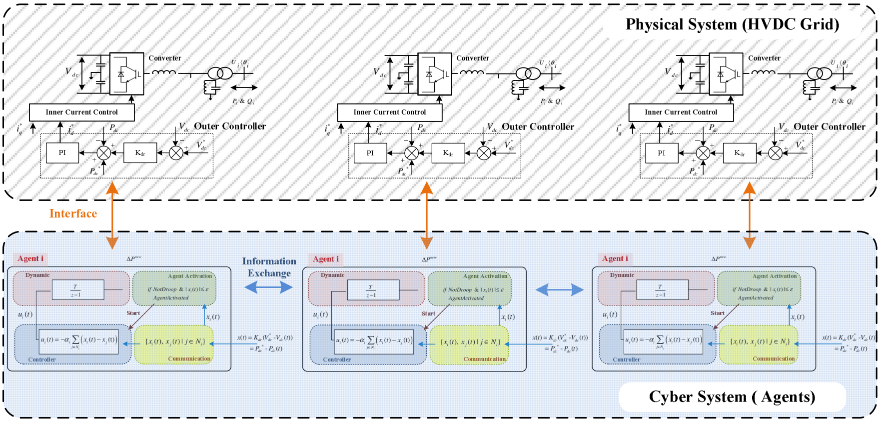

Fig. 9 Agent based control in Cyber-Physical System Framework

As shown in Fig. 9, the control model and process has been separated into two parts. The physical system consists of power system, both AC and DC grids, and the corresponding local control system for each converter station. In this study, the local control system including the inner and outer control level are presented as part of the physical system. However one is possible to consider this local control system as part of cyber system as well, but due to simplicity in the modeling of the system, this assumption has been made in this study.

3.2 *Modeling the Communication System*

This section explains the multi-agent control scheme developed. The agent's setup, system dynamics and the information link between agents are studied with different tools. Graph theory is one of the tools often used to model the agent's data exchange interactions [26]. Consider a graph *G= {V, e}* consisting of a set of vertices or agents *V= {1,..., N}* and edges *e*. Nodes *i* and *j* are adjacent if a link or edge is between them. The adjacency matrix *A* that shows the adjacency between the nodes in the graph *G* can be defined.

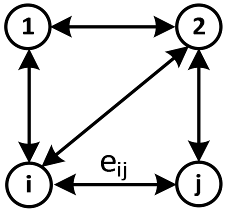

Fig. 10 Information graph G with links e

The distance between two nodes i.e. *d(i,j)* is the shortest path with least number of links that connect nodes *i* and *j*. The degree matrix *D* with the elements of d_i is a diagonal matrix which elements are the cardinality of agent *i* neighbor set $N_i = \{j \in v : (i, j) \in \varepsilon\}$. The Laplacian matrix L is equal to the difference between degree matrix and adjacency matrix *(L=D-A)*. Consider an undirected graph (see Fig. 10), since the Laplacian matrix is symmetric and positive semi-definite i.e. the sums of the elements in each row is zero, the first eigenvalue of the matrix is equal to zero ($\lambda_1(\mathrm{G}) = 0$). For a connected graph, Laplacian matrix *L* has exactly one zero eigenvalue and the eigenvalues increases by the order i.e. $0 = \lambda_1(g) \le \lambda_2(g) \le ... \le \lambda_N(g)$. The second smallest eigenvalue $\lambda_2(\mathrm{G})$ of L shows how well the graph *G* is connected. Therefore it is also known as the algebraic connectivity [27].

3.3 Control Algorithm

As mentioned earlier, in the case of any disturbance or power mismatch in a typical DC grid, some converters can be assigned to contribute in power sharing by using DC voltage droop control (distributed DC slack). The assignment of droop parameters for different converters is a real-time problem that must be recalculated for any new system status based on converter capacities, market issues or line limitation. If droop parameters are not reassigned correctly, the next disturbances can drop the voltage level of the entire system to the minimum or maximum limit. In this situation, other converters that work on power constant mode will produce more to recover their DC voltage. Instead of centralized controller to assign the new droop parameter for the converters and decide the fairly power sharing in the new state, this section purposes a distributed agent-based scheme for power sharing and recover the DC voltage level after the disturbance.

As it is shown in Fig. 11, the agent set-up consists of four parts. The communication part is responsible for receiving measurements from the neighbors. The difference in current DC power measurements and pre-defined references is the state of the agent. The controller part is responsible to create the distributed control law. In this study, we use $u_i(t) = -\sum_{j \in N_i} \left(x_i(t) - x_j(\mathrm{t}) \right)$ as the distributed control law, where x_i is the local state variable and x_j is the state variable of neighbors. This can be changed based on the designer's interest. The dynamic block is the agent's dynamic behavior that here, is a single integrator agent ($\dot{x} = u$). The last block is the Agent Activation that senses a new operating point, DC voltage drops close to limits, and sends the commands to start the agent or freeze the droop control.

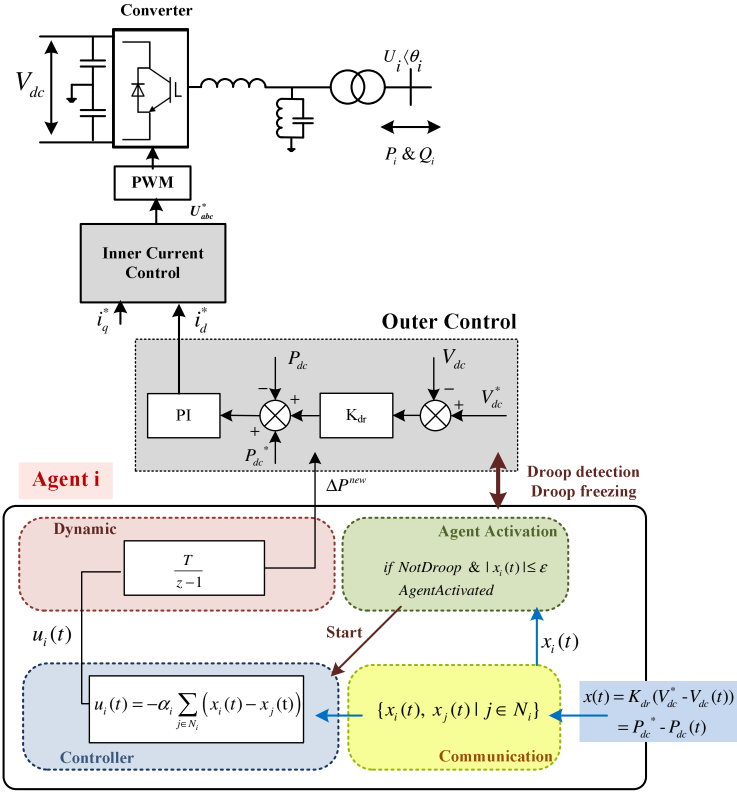

Fig. 11 Agent-based control set-up

The agents start the information sharing either when the DC voltage drop/increase is close to limit or when they are manually set to power consensus. So, when the DC voltage drop/increase is recognized, the agent freezes the DC droop control, increases the voltage level by pre-disturbances value, and finally starts the communication with other agents to converge to agreement. The agreements value is the average of initial value of the agents' state after start i.e. $\Delta v_i(\mathrm{t}) \to \frac{1}{N}\sum_{i\in v} \Delta v_i(\mathrm{t}^+{}_{disturbance})$.

Proof:

If we consider the set of single integrator agents that are connected through an undirected graph g, the closed loop system becomes $\dot{x} = -L(g)x(t)$, *where L is the Laplacian of the graph. The solution of the dynamic for each agent contains the exponential term with the decay rate depending on this matrix i.e.* $x(t) = \mathrm{e}^{-L(g)t}\, x(0)$. *Assume U is the matrix consisting of normalized and orthogonal eigenvectors of matrix L, and V the diagonal matrix comprises of eigenvalues of the matrix. Then it is possible to expand the exponential terms of the system response using the spectral factorization of the Laplacian as follows:*

$$\mathrm{e}^{-L(g)t}\mathrm{x}(0) = (\mathrm{e}^{-(UV(\mathrm{g})\mathrm{U}^T)t})\,\mathrm{x}(0) = (U\,\mathrm{e}^{-V(\mathrm{g})t}\,U^T)\,\mathrm{x}(0)$$
$$= \mathrm{e}^{-\lambda_1(g)t}\,u_1^T x(0)u_1 + \mathrm{e}^{-\lambda_1(g)t}\,u_2^T x(0)u_2 + \ldots + \mathrm{e}^{-\lambda_1(g)t}\,u_n^T x(0)u_n$$

As mentioned above, for the connected graph the first eigenvalue is zero and higher orders have the positive values. So, the exponential terms with positive eigenvalue (negative rate) will decay by time. The smallest positive eigenvalue $\lambda_2(\mathrm{g})$ *dominates the slowest rate of convergence in the solution. Based on system solution, when the time goes to infinite, the respond converges to the average value of the initial states. The detail of the proof can be found in [28].*

$$x(\mathrm{t}) \to u_1^T x(0)u_1 = \frac{\mathbf{1}^T x(0)\mathbf{1}}{n}$$

4 Use case – 7 Terminal HVDC Grid

This section presents a case study acting as proof of concept of the proposed Multi-agent control scheme. The section begins with a presentation of a DC grid used for the study including all relevant parameters. Thereafter the co-simulation platform used to study the control scheme is presented. Finally the results of the study are presented at the end of the section.

4.1 System under Study

In order to validate the suggested agent-control algorithm in the previous section, a 7-terminal DC grid has been developed in a real-time simulator. Since there is not any standard model or real system available for DC grid studies, the chosen model is designed based on the system data for a 7-terminal DC grid analyzed in [29]. The multi-terminal HVDC system consists of seven converter stations. As shown in Fig. 12, the converter stations are connected through a meshed DC grid. The line parameters are defined in TABLE I.

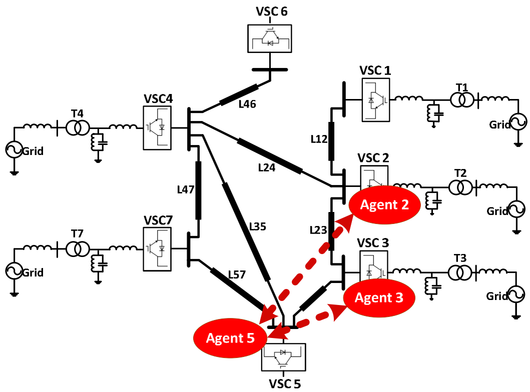

Fig. 12 7-terminal VSC-HVDC transmission grid

The average model has been used to model the VSC stations. So the dynamic of the switching and corresponding effects are not considered in this study since the control scheme is developed for higher system control. Each converter is connected to a separate strong AC grid. The modeled VSC stations can control active power or DC voltage on DC side, and reactive power or AC voltage on AC side. The power ratings and control modes of the stations are provided in TABLE II.

Table 1 DC grid line parameters

Lines	$R(\Omega)$	$L(mH)$	Length (Km)
L12	2.577	22.5	213
L23	3.00	26.2	248
L24	2.50	21.9	207
L35	4	25.0	331
L45	1	8.76	83
L46	2.5	21.9	207
L47	3.5	30.5	289
L57	2	17.4	165

Table 2 Converters Rating and modes

Converter	Capacity (MW)	Control mode	Agent Control
1	200	Active Power	NA
2	300	DC droop Voltage	Implemented
3	150	DC droop Voltage	Implemented
4	200	Active Power	NA
5	300	DC droop Voltage	Implemented
6	100	Active Power	NA
7	50	Active Power	NA

As shown above, three converters (2, 3 and 5) out of seven terminals are interacting with the agents. And in this specific set-up the tree connection is considered between these three agents in the system. Converter 5 is able to exchange the data with both converters 2 and 3. The reflected graph is an undirected graph meaning that both nodes at the end of each edge are able to send/receive the data to/from other node.

4.2 Simulation Platform

The Power System Management and Information eXchange (PSMIX) Platform is 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 (see Fig. 13). This real-time platform reflects the characteristic of the supporting ICT system and the physical process, as well as the interfacing devices or systems as close as possible to the real life scenarios. PSMIX is a general real-time architecture that can be re-arranged for different studies from distribution grid control scenarios to wide area control of transmission grid. This platform includes real-time power system simulator, real-time communication network simulator, applications, and software-based or real interfacing devices/measurement. The main factor in the development of any 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 [25]. For this study, the PSMIX Platform is configured to support the modeling of HVDC grid and its supporting control and communication system. The detail information of the components is described as follows.

OPAL-RT eMEGAsim Simulator

The eMEGAsim is a commercial real time simulator which combines OPAL-RT electrical circuit solvers, SimPowerSystem and RT-LAB distributed processing software and hardware for high speed real-time simulations of a 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 DC grid presented above has been modeled and simulated in this simulator.

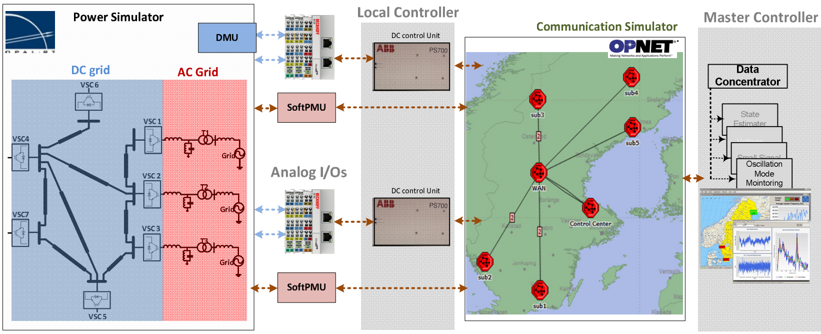

Fig. 13 PSMIX Platform Architecture

Measurement Units
The HIL feature of the OPAL-RT simulator enables the simulated power grid to interact via analog I/Os. This HIL simulation test platform provides the ability for more realistic study of the real world systems. Since the HVDC controller is able to communicate with specific analog I/Os, a special DC measurement unit (DMU) has been developed inside the OPAL-RT simulator to send/receive the DC voltage and DC power measurement with specific accuracy to/from analog I/Os. This device takes in the analog input in the range of 0V to 10V and digitizes it with 16-bits resolution. To provide the input to the simulated power grid 4-channel analog output device is used. This device generates the voltage signal within the range of -10V to 10V. Both I/O devices are mounted on an EtherCAT coupler which provides the means of communication between I/Os via the EtherCAT protocol providing sufficient performance. For the AC side, a Software-based Phasor Measurement Unit (SoftPMU) has been developed (See [25] for detail information). The specific method proposed in this chapter only uses the DMU for control purposes.

HVDC Industrial Controller
ABB's MACH3 system is a high performance control and protection system includes an industrial computer called PS700 which runs Windows embedded integrated with INtime reliable Real time operating systems (RTOS). PS700 communicates with the analog devise via EtherCAT protocol. It can communicate with other HVDC industrial control systems via Ethernet. HiDraw studio is a graphical programming environment based on C++ that is used to program the HDVC station control systems hardware. When the project in HiDraw is compiled, first the C++ code is generated then this C++ code is compiled and released for executing in INtime. The agent logic has been developed in C++ codes in HiDraw.

OPNET Communication Network Simulator
OPNET is a communication system modeler which provides comprehensive development environment for modeling communication networks and distributed systems. The behavior of the simulated communication network can be analyzed

by performing discrete event simulations. OPNET contains the System-in-the-loop (STIL) module enabling the connection of the simulation model with live network hardware by providing interfaces and modules [30]. For the platform presented in the chapter each STIL module inside the simulation environment is assigned to a specific network adapter on the machine. There are four such physical network adapters available. Each of the three PS700 has been connected to these adapters to simulate three HVDC control stations located at different geographical locations.

Master Controller: KTH PowerIT Platform
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 [25]. Besides, it is able to receive the DC grid information i.e. DC voltage and active power from the converters (PS700 controller) using industrial defined Raw 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 in this particular agent-based control scheme, there is no need of a centralized application to be run on the PowerIT platform.

4.3 Agent Logic and Information Exchange Modeling

The agents' logic has been modeled using HiDraw language, then compiled and implemented in HVDC controller (PS700). The Communication network model considered for this case study consists of just three subnets. This communication network mirrors the information exchange graph of the agents that is a tree graph. Since just three agents are assigned for the power sharing coordination, the communication networks model consists of three subnets. Each subnet represents an HVDC substation and is connected to corresponding HVDC controller through a physical Network Adaptor and SITL gateway. Therefore, the generated traffic by the real controller can be passed to the communications simulator. In addition, the SITL gateways must be configured properly to filter other packets and receive only the relevant packets. The initial network model between the agents is built based on the empirical data from an industrial project [31]. This network is a dedicated network that uses the fiber optic links. The link bandwidth is considered to be 24 Mbps.

4.4 Simulation Results

Scenarios
Several scenarios have been implemented to evaluate the performance of agent-based control schemes in different conditions. In the original set-up, three converters of 1, 4, 6 and 7 are set to control active power, and other three of 2, 3 and 5

are set to DC droop voltage control. The droop coefficients in the first scenario are set to 0.75, 1 and 1.5. In the agent-based set-up, the three converters of 2, 3 and 5 use the proposed schemes to bring back the DC voltage to normal limit and share the power mismatch equally in terms of the power capacity in per unit by using on local and neighboring information. In the first step, these two different set-ups are compared for the case that the droop control is not sufficient for series of events (scenario I). In the second step, the droop control and agent-based power sharing are evaluated for normal operational scenarios in which the voltage limit is not hit (Scenario II). Besides, the performance of agent-based control scheme is evaluated for different bit error rate (BER) on the communication link (scenario III). In scenario I, the active power injection in converter 6 is reduced to 0.6 pu after 5 seconds and to zero after 21 second. In scenario II and III, a disturbance is introduced to the HVDC grid by decreasing the active power injection in converter 6 to 0.4 pu after 5 seconds. And, the second disturbance is introduced in 21 seconds by decreasing the injection of converter 6 to zero. Note that the per unit values for each converter is based on the station power capacity, not the system base. Besides, to evaluate the performance of the real-time co-simulation platform, the first scenario is also fully implemented just in the real-time power simulator. This scenario is called "simulation scenario" from now. The difference of this scenario and "co-simulation scenario" is the environment of modeling. In "simulation scenario", in contrast to co-simulation scenario, the physical power system, control system and communication system are modelled in just one real-time simulator i.e. OPAL-RT simulator. In this scenario, the communication network is modeled with a simple delay block. Note that a tree graph is considered to exchange the information as a minimum connectivity requirement.

Results

Fig. 14 depicts the result of scenario I. The results show that after the first disturbance at 5 seconds, the voltage drop is significant if the Droop Control is used. But still the system remains reliable. Now, with the second disturbance, the voltage level of the system drops to the limits of some converters such as converter 4. Consequently, this converter starts in power sharing even if it is set to just follow its scheduled power (power constant control). On the other hand, the agent-based control first brings the voltage level to pre-disturbance situation and then shares the power mismatch fairly.

The result of power sharing in both cases i.e. droop based and agent-based (scenario II) are presented in Fig. 15. The agents ordering the HVDC converters are sharing the information to come to average power contribution. The result shows that it takes around 5 seconds for the converters to reach the average value. It can be seen that the consensus value is basically the average of power outputs in the droop control scheme.

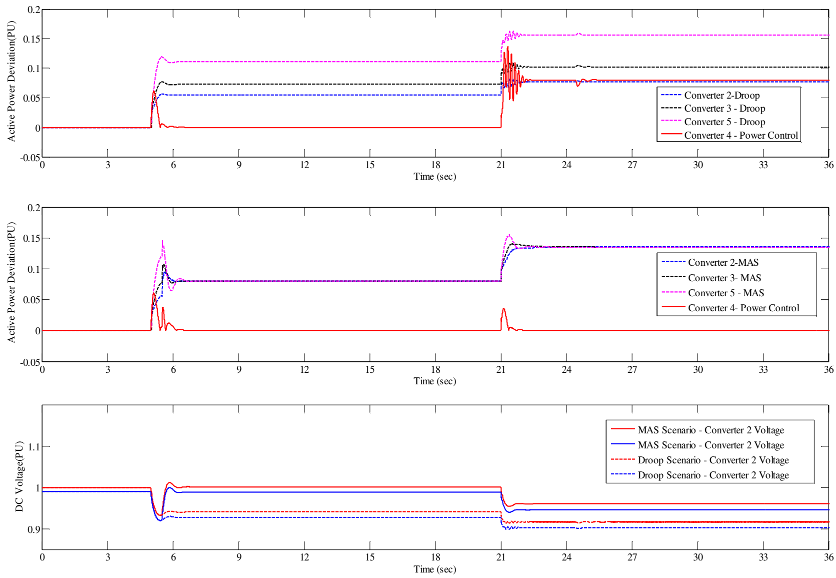

Fig. 14 Comparison of Droop Control and Agent-base Control

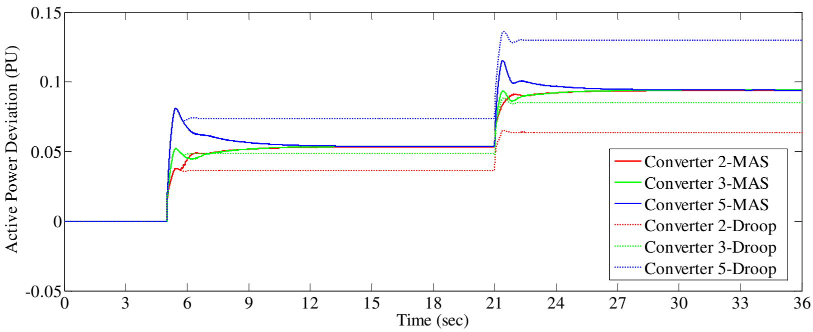

Fig. 15 Consensus-based versus droop-based power sharing

Fig. 16 shows the result of scenario II. As the benefit of having communication simulator in the simulation loop, the BER can be studied on the control scheme. As shown here, during the first disturbance the BER is around 0.01 percent and the controller cannot recognize the information, and when BER reaches approximately 0.004 percent the agents recognize the information and try to reach the consensus value.

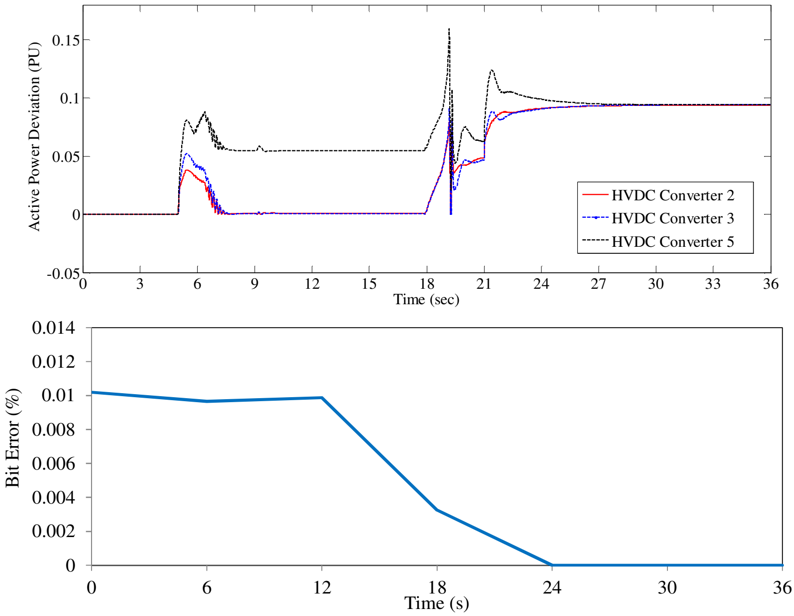

Fig. 16 Impact of BER on the control performance

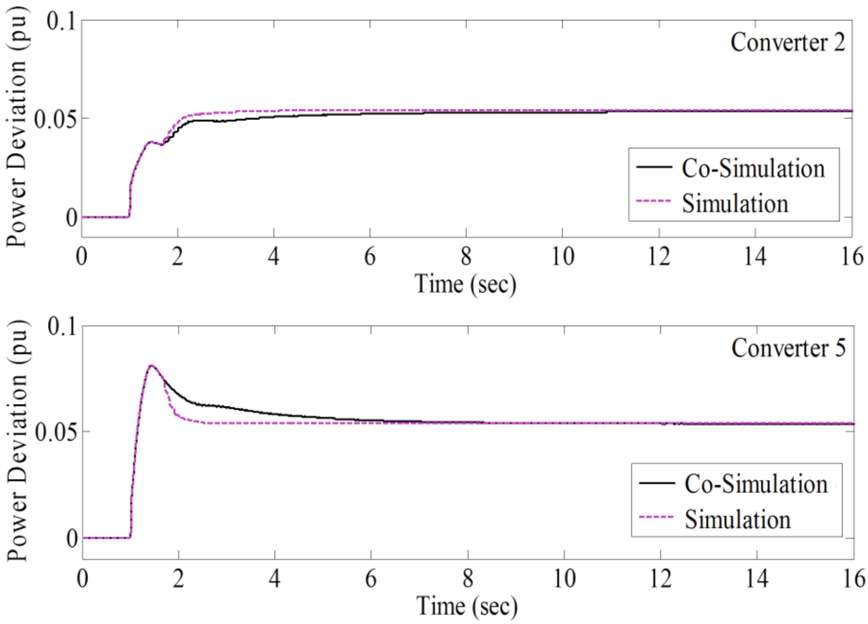

Fig. 17 Result of Simulation and co-Simulation

The comparison of simulation and co-simulation implementation is presented in Fig. 17. The result shows that some dynamic of the real controller and errors in A/D conversion cannot capture in the pure simulation. However the study shows that both results in steady state and in their trend follow each other. It can be concluded that when the studying cyber physical systems, it is uncertain to use a pure simulation to model the whole system.

5 Conclusion

The integration of large-scale renewable energy sources, the inter-connection of grids to neighboring national grids and the limitation in the expansion of new AC transmission line draw the power system planners' attention to move toward HVDC technology with its various benefits such as the visual impact, controllability and lower power loss. Different researches have been carried out to evaluate design and control choices for operating the HVDC grids.

This work presented an agent-based method to coordinate the power sharing in an overlaid HVDC grid. The method has been compared with the existing Voltage Droop Control. The proposed method uses the distributed control law based on local and just neighboring converters to contribute the power between the converters in the case of power deficiency. In contrast to droop control, it does not need to recalculate the coefficient for new operation point. This method regardless the type of DC grid operational architecture (Independent DC TSO or integrated TSO) can be implemented to control the power flow in distributed manner in the HVDC grid. The results showed the advantage of the proposed method. However, the performance of the control scheme can be degraded by communication network parameters.

The study and evaluation of this control scheme has been tackled from the cyber physical system (CPS) perspective. The agent/computational entities and information exchange between them has been modelled as a cyber-system interfacing the physical power system. A real-time co-simulation platform has been developed to evaluate the impact of IT supporting system (cyber system) on the operation of the HVDC grid. In future, this platform using distributed decision makers can be used for more advances functions such as distributed optimal power flow calculation.

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