Examination of Different Communication Topologies for Distributed Control of Multi-terminal HVDC Grids

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Summary
This paper discusses different communication topologies for cooperative distributed control design of a multi-terminal DC (MTDC) network. In the discussed architecture, the objective of the control design is the DC node voltage control of MTDC grids in different topologies. In DC systems, the DC node voltages are the most important measure, which define the system state and power flow. In this paper, each converter corresponds to an agent in cyber layer, and each agent only requires the node information of neighbor agents in addition to its own information. In distributed control fashion, the necessities of having central controller and complex communication are eliminated. The indispensable monitoring and supervisory systems for MTDC grid provide local sensing-communication capability thereby using local information and coordinating the voltage control in a distributed manner make design and implementation of a cooperative control feasible. The performance of the different type of communication topologies are examined on an eight-terminal MTDC system connecting four offshore wind farms to the four independent onshore grids.

Key words:
Distributed cooperative control, multi-agent systems, MTDC systems, DC grid operation, Voltage source converter.

1. Introduction

The increasing electricity demand, environmental concerns and possible shortage of conventional energy sources such as fossil and nuclear energy refer studies to find and utilize alternative energy sources. The development of wind, solar and other renewable energy sources, however, have lead to urgent need to integrate these decentralized power plant into grid in an economical and environmentally friendly way. Even though, AC transmission is accepted as a mature technology in today's electrical power systems, the capability of transmitting bulk amount of power over long distance even for among asynchronous networks with higher efficiency make the DC transmission more appropriate for integration of large quantities of renewable energy into main grid. These days, there is an growing number of offshore wind farms, which are located tens or hundreds of miles off shore and integrated in the main grid through submarine cables [1]. Offshore wind power plants can be designed in different scenario such that multiple generators connected to a single power converter or each wind turbine coupled with a power converter. [2]. The inclusion of the large offshore wind power plants into the main grid in need of building dc networks with more than two terminals has led to emergence of the topic voltage source converter (VSC) based high voltage (HV) MTDC. Two different HVDC technologies are available in current literature. The current source converter (CSC) based HVDC technology using thyristor has many application sample around the world with regard to VSC based technology using gate turn-off thyristor (GTO) [3]. The most salient feature of the VSC technology over conventional CSC is the relatively simple extension to multi-terminal topology [4]. Actually, the inherent technical features of the CSC make a multi-terminal operation impractical if more than three converters are involved. Therefore, CSC based HVDC systems have been designed pointto point so far. On the other hand, VSC based systems, in addition to its multi-terminal operation capability, can independently control active and reactive power. VSC based technology also obviates the necessity of having external voltage source for commutation. The capability of connection to weak AC systems, the features ordered above, and current power system's insufficiency in terms of transmission capacity have led to an escalated interest in transmission network with VSC based HVDC technology. However, VSC based transmission have higher power loss and high cost compared to the CSC based HVDC systems. The further investigation from a technical perspective outlined in [1], [3], [5]–[7]. Also, different circuit topologies of multi-terminal HVDC systems were discussed in [8].

While the attention on MTDC network is escalating, this field is still needed to discuss and enhance further especially for their control techniques and operation specifics. Since DC voltage is the most significant measure that also directly related to power dispatch and flow, its regulation is the main challenge similar to the frequency in AC grids. In contrary to frequency as a global parameter in AC grids, the DC voltage in grid varies throughout the network according to the power injection at each node. Since the standardization process of the DC voltage control regulation has not been done yet, the centralized control or decentralized control, or combinations of both have been utilized in MTDC studies [1], [2], [9]-[21]. The master-slave, voltage margin, and voltage droop methods are elaborately exmanied strategies for DC voltage control in MTDC grids. Whereas voltage regulation task can be shifted among several VSCs in the

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Manuscript received February 5, 2019
Manuscript revised February 20, 2019

voltage margin strategy, always one VSC is mandatorily responsible for controlling the voltage profile [22]. In the case of master converter failure, the dc voltage is lost which means that reliability and resilience is poor in this method. However, the voltage margin method, which can be seen as an extension of the master-slave control and able to overcome this kind of problem, suffers from oscillations at time converter shifting [23]. The voltage droop control is the mostly employed strategy for DC voltage control in the MTDC grids. The contribution of the several converters to the DC voltage control of the grid make this approach more reliable respect to master-slave control and does not give rise to voltage oscillations as occur in voltage margin control [24], [25].

The voltage droop strategy in decentralized fashion has been widely used in MTDC without communication link [17], [15], [10], [12], [16]. A generalized droop control structure is proposed in [19] to interchange between DC voltage control modes, which make full power flow control with fixed real power and fixed DC voltage of the converters available, based on the MTDC grid parameters. In [16], proposed control design is built on the frequency-response analysis to select proper droop gains, taking into account the performance specifications. Nonlinear control design based on dynamic feedback linearization control theory and a backstepping like procedure is presented for three terminals MTDC grid to check stability of the system in [13]. Impact of DC line voltage drops on the droop coefficients is addressed in [26]. In [25], a scheme for adapting the droop coefficients to share the burden according to the available headroom of each converter station is proposed. In order to eliminate the need for communication between the DC terminals, Eriksson presented a control structure that perform DC voltage feedback loop shaping to modulate the power in one terminal and let the other terminals react on the DC voltage change [20]. In [10], authors proposed a systematic design procedure that is reduced to solving a convex optimization problem with linear matrix inequalities in order to compute the droop gains ensuring stability and minimizing the effect of disturbances on the DC voltage. In [14], a generalized droop control strategy is proposed to realize autonomous coordination among converters without the need of communication.

However, [2] presents the power flow optimization problem to be addressed by a centralized controller and emphasizes that the minimization of the power losses cannot be achieved without communication. The hierarchical optimal power flow control in MTDC is addressed in [13], the lower level control is based on conventional droop control whereas the upper control level mainly uses power flow optimization algorithm in a centralized fashion to minimize the power loss. Zhu et al. propose advanced communication based coordinated control strategy, which is underpinned by a wide area, and supervisory control and data acquisition system, in order to enhance network voltage stability and facilitate flexible power dispatch.

Gavriluta et. al. in [27], propose a hierarchical control architecture where primary control is decentralized and implemented using generalized droop method whereas its secondary control is centralized and regulates the operating point of the network so that optimal power flow is achieved. In [23], they replace centralized secondary control with a fully distributed, agent based approach in order to improve resiliency and reliability of the system.

The communication requirement of centralized control systems is more complicated for MTDC networks whose terminals are hundreds kilometers away from each other. Moreover, reliability, higher cost concerns, more communication latency, and lack of self-organizing and scalability are serious drawbacks of centralized controls compared to decentralized one [28]. Applications of the distributed cooperative control in power systems as a decentralized control system have been detailed in literature [28]- [34].

In this paper, the examination of different types of cyber layer for distributed cooperative control of multi-agent systems is carried out to check their feasibility with respect to different MTDC topologies. In this study, each converter represents an agent, and each agent is represented by a node on a communication graph. In contrary to centralized control method, distributed cooperative control only requires a sparse communication network spanned through the MTDC topology, and loss of the communication link does not lead the system to collapse as long as the remaining communication graph is connected.

This paper organized as follows. Section II presents the advantages and drawbacks of different control architectures. Section III introduces the distributed control methodology. Section IV presents the different physical layer of multi-terminal HVDC. The simulation results of the study over 8 terminal MTDC grids in different topologies are discussed in Section V. Section VI concludes this paper.

2. Different Control Architectures

It is better to start with categorizing different control strategies such as centralized, decentralized and distributed. In centralized control architecture, there is main unit that gathers all information from all the nodes, and the embedded algorithm in it does calculations which will be sent to nodes back as command to realized. The most of the calculations is carried out in this unit and it works as decision maker. This architecture is the commonly used method in current power systems applications, since its advantages such as having an global overview of all the system. However, this approach is neither easily extendable nor computationally scalable. Furthermore, the reliability level is quite low in case single point failure occurs. On the other hand, some of the participating actor may want to keep their confidential data secret, the implementation of central control in such situation is not possible.

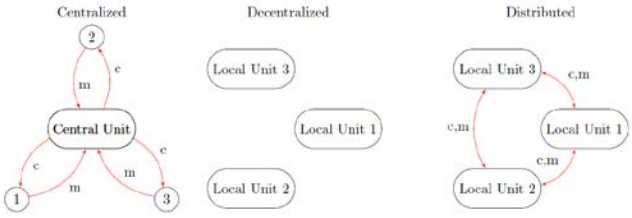
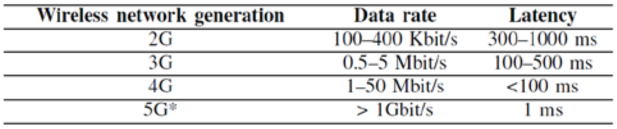


Fig. 1 Different Control Architectures.

In decentralized control architecture, each node is able to evaluate local state and make decision, however there is no coordination or information exchange between nodes. This kind of system is easily scalable, and extremely robust in case failure happens. On the other hand, this approach never guarantee global optimality. The droop control as a primary control in power systems is well known example of decentralized control approach.

The distributed control architecture lays between the centralized and decentralized approach [27]. In this approach, each node can evaluate and control its states as it is done in decentralized fashion, but it also have ability to exchange information and commands among its neighbors as it occurs in centralized one. This system is easily extendable, scalable, and reliable. Moreover, the growth of the system provides resiliency and robustness. The main drawback of this approach is that its in need of having communication link that sometimes have intense data flow between nodes. Nevertheless, failure of one of the communication link does not draw all system collapse.

Table 1: Performance of Communication Networks regarding Data Rate and Latency



Wireless network generation	Data rate	Latency
2G	100–400 Kbit/s	300–1000 ms
3G	0.5–5 Mbit/s	100–500 ms
4G	1–50 Mbit/s	<100 ms
5G*	> 1Gbit/s	1 ms

as long as it has spanning tree. However, this is true only for a centralized system, where the central controller fails to find a solution if the communication with one of the nodes fails. In the case of a distributed approach, it is still able to maintain to operate even communication link could fail several times. In [35], it is shown that a distributed microgrid control strategy is two times more tolerant to communication delays than a centralized approach. In terms of maintaining performance under data loss conditions, according to the same results, the distributed controller remains stable even under drastic conditions such as 95 % packet loss performance that the central controller is not able to match. Therefore, the only drawback of distributed control method might be disregarded with having tolerance ability and modern communication networks. Table I represents the actual values of data rate and latency in modern communication networks depend on the type of service.

3. Model and Problem Setup

Let $\mathcal{G}$ be a graph. An undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with $\mathcal{V} = \{v_1, ..., V_n\}$ a set of $\mathcal{N}$ nodes , each having a state x_i defined as the voltage at that node. Let there be K root or source nodes y_k, k=1,...,K, each with a directed edge into one node in the graph. The current flows into node i due to voltage differences $(x_j - x_i)$, with $j \in \mathcal{N}_i$ its neighbors that have edges in common with node i. The algorithm in order to find local update law for node i is Kirchhoff's current law,

$$\dot{x}_i = \sum_{j \in \mathcal{N}_i} a_{ij} \left(x_j - x_i\right) + b_{ik}(y_k - x_i) \qquad (1)$$

where the right-hand side is the sum of the currents flowing into node i. It has been considered that a unit capacitor is connected from each node to ground and the element flow equation $\mathcal{C}\dot{v} = I$ is used to relate net current I, voltage v, and capacitance $\mathcal{C}$=1 at each node. In this equation, some nodes have external voltage sources y_k , k =1,...,K delivering current directly to them through links with conductances b_{ik}>0. This equation can be written in global form in order to simulate,

$$\dot{x}_i = -(L + \textstyle\sum_k b_k)\, x + b_y \qquad (2)$$

where y and B refer to external voltage sources and diagonal matrix that has the impedances between each node and external voltages, respectively.

A MTDC system consisting of n DC buses, denoted by the vertex $\mathcal{V}$ = {1,....,n}, see Fig.2 for an example of a MTDC topology. The DC buses are modelled as ideal current sources which are connected by m HVDC transmission lines, denoted by the edge set $\mathcal{E}$={1,...,m}. The dynamics of any system connected through the DC buses, or any dynamics of DC buses. The HVDC lines are assumed to be purely resistive, implying that

$$I_{ij} = \frac{1}{R_{ij}} \left(V_i - V_j\right) \qquad (3)$$

due to Ohm's law, where V_i is the voltage of the bus i, R_{ij} is the resistance and I_{ij} is current of the HVDC line from bus i to j.

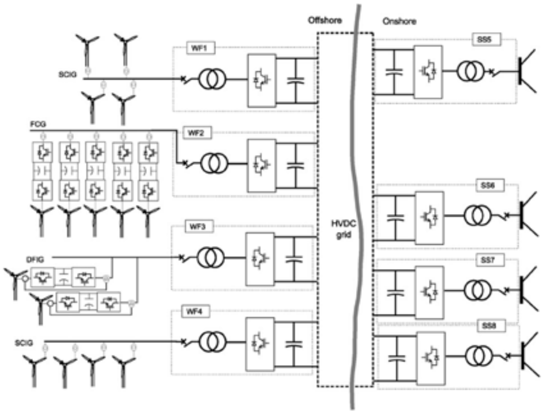


Fig. 2 Multi-terminal HVDC based on VSC.

4. Multi-Terminal HVDC Topology Analysis

In order to transport bulk amount of power from large offshore wind farm into main grid, different MTDC topologies such as point-to-point, general ring (GRT), star (ST), and star with a central switching ring topology (SGRT) with HVDC systems can be used. The point-to-point topology is depicted in Fig.3. This topology based on multiple point-to-point connection that does not create a connected graph in terms of graph topology. In the case of having fault in any converter, the best action is to disconnect the faulted line using the AC circuit breakers and trip off on over speed or DC link over voltages of wind turbines. If fault occurs on a line, the connection between two points will be lost. This configuration, therefore, is not flexible in terms of operation and graph topology.

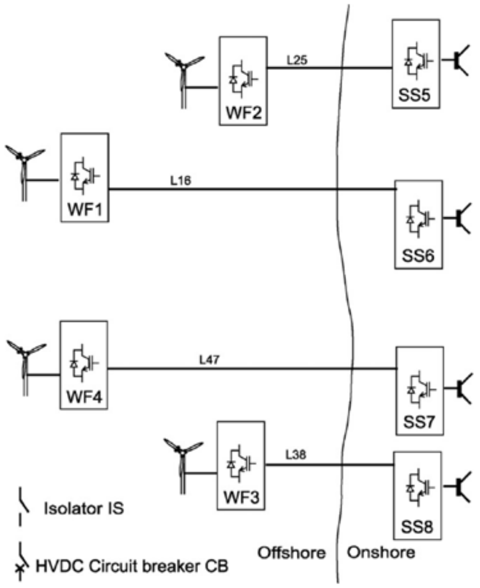


Fig. 3 Point-to-point topology.

The GRT based on connected nodes with a loop that is called ring is given in Fig.4. This topology has flexibility to operate under both open and close loop conditions. In order to coordinate operation configuration, fast communication network is needed. From graph structure perspective, it has superiority regard to point-to-point topology since it is connected graph.

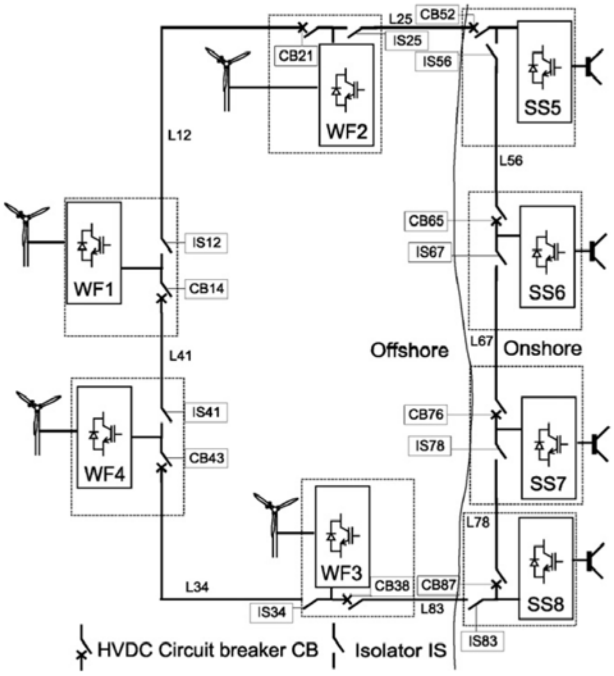


Fig. 4 Star with a central switching ring topology.

The star topology (ST), shown in Fig. 5, is a multiterminal HVDC system where each line that is connected to a wind farm or a substation is connected to a central star node [8]. The main disadvantage of the configuration is that having a fault at the central node cause entire system collapse. Even though, this configuration have various advantages, the flexibility is not as good as GRT.

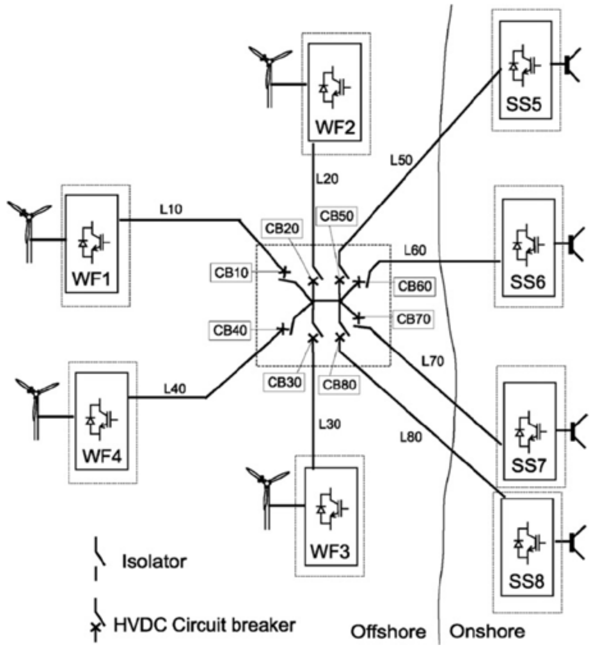


Fig. 5 Star topology.

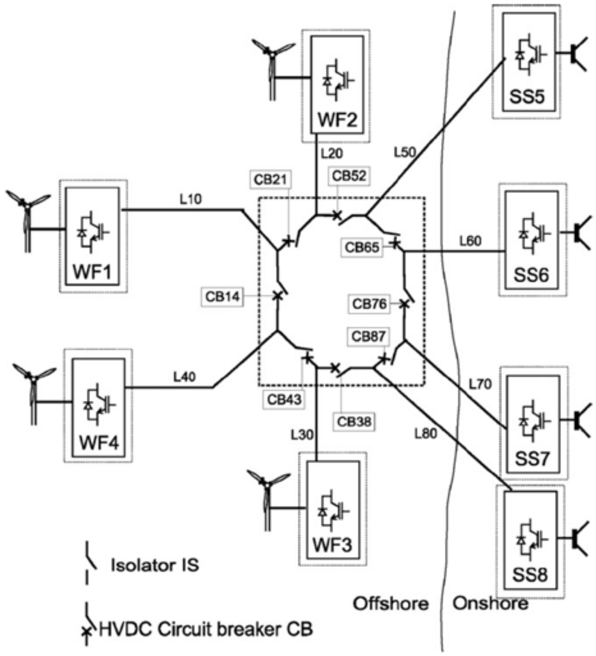


Fig. 6 Star with a central switching ring topology.

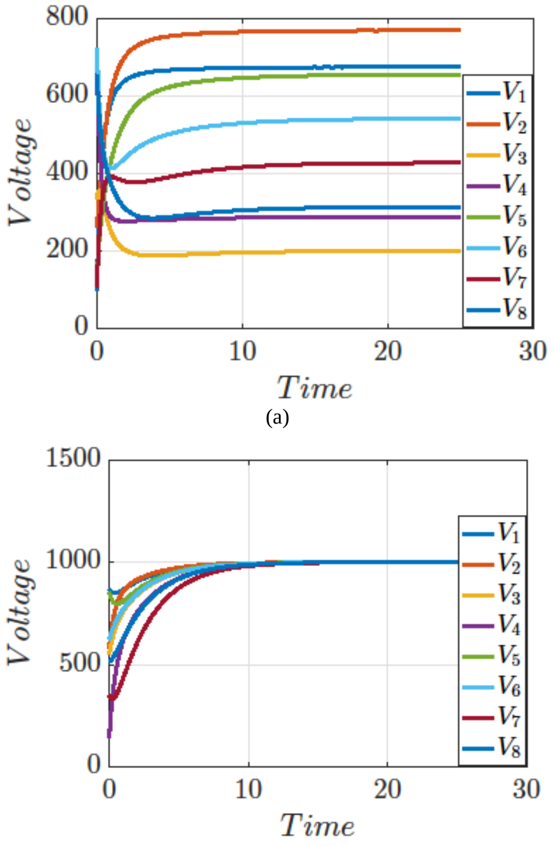
The combining of GRT and ST come out as a new topology called as SGRT shown in Fig. 6. This topology has the same drawbacks as ST has, but it shows more flexibility under short and long-term line faults.

5. Simulation Studies

An eight terminal MTDC network, proposed in [8] as possible topologies for integrating the wind power into the main grid, was used for simulation studies.

Four different topoloies were addressed in order to evaluate their graph topologies in terms of their convergence rates, either consensus or steady state values depend on the case studies. Fig. 7 shows that four different graph topologies, which are generated from the MTDC topologies, have different convergence rate when all wind farm side converter inject power at 1000 V.

In Fig.7, the convergence of different graph topologies namely point-to-point, central ring, star, and star with a central switches were depicted. The voltage at all nodes are converged to 1000 V for point-to-point and central ring topologies, however other topologies reached to steady state at around 980V since their impedances between external sources and node are higher than other topologies. For star topology and star with a central switching topology, impedance values are chosen higher since their distance between source and node are longer.



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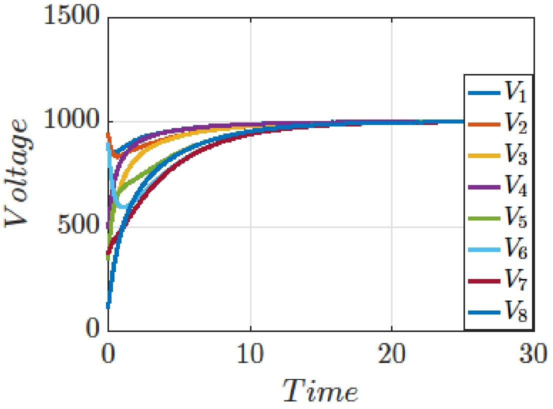

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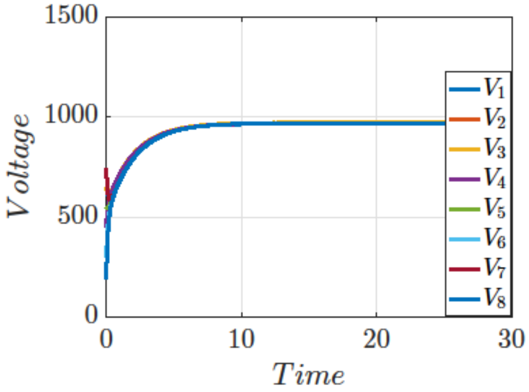

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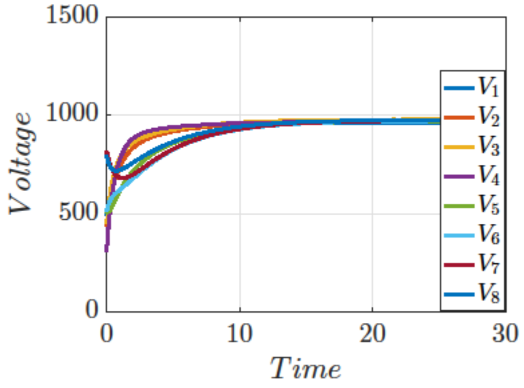
Fig. 7 Node Voltages for Different Graph Topologies.

Fig. 8 shows the case when some of the external voltage source is out of service. In this case, the corresponded node behaves like there is no external voltage sources at that node. The steady state value reach to consensus at the voltage of the bus, except point-to-point topology, since it is not strongly connected graph topology.



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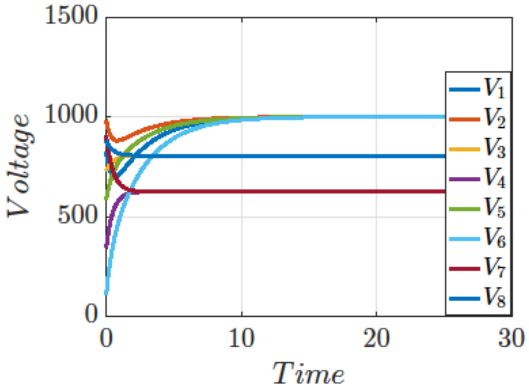

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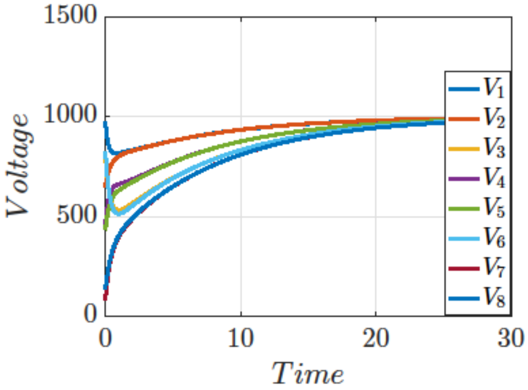

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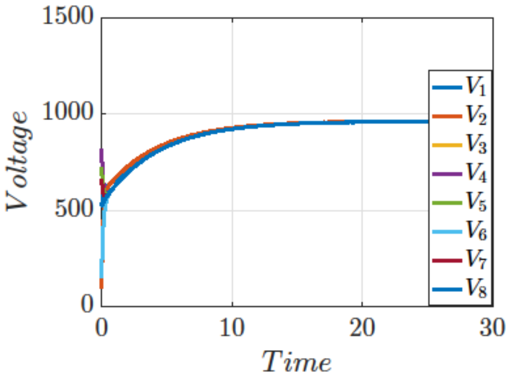
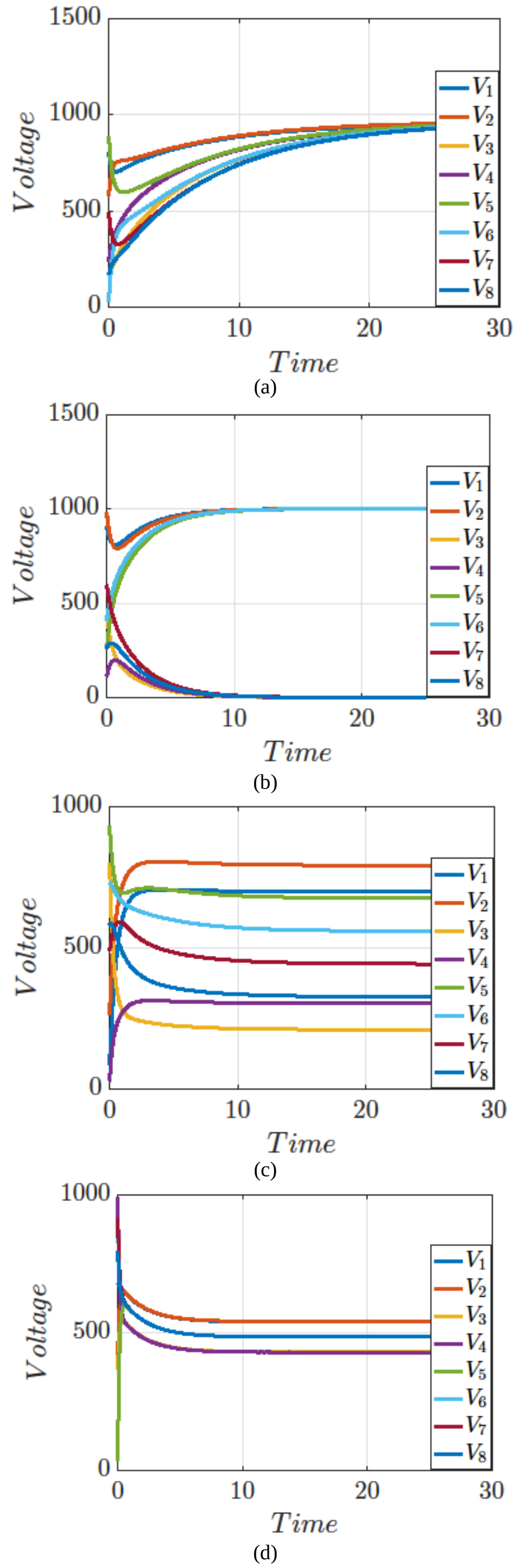


(d)

Fig. 8 Node Voltages for Different Graph Topologies in case some of the source is out of service.

In the case of having external voltage with zero node voltage is given in Fig.9. As we expected, the steady state value for each node is scattered among the set value of the other external voltages. In the point-to-point to topology, the nodes that have zero voltage draw corresponded terminal voltage to zero as well.



(a)

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Fig. 9 Node Voltages for Different Graph Topologies in case some source voltage set zero.

The star topology has better convergence rate and less oscillation with respect to other topologies. Under normal operation condition, point-to-point topology shows less oscillations than central ring topology.

6. Conclusion

In this study, different MTDC topologies are considered as cyber layer of the corresponded MTDC in order to evaluate performance of the different type of communication topologies on an eight terminal MTDC sytem. Studies show that the voltage regulation of MTDC can be carried out using one of the examined cyber layer, except point-to-point regarding distributed control strategy. Despite star topology gives better convergence rate, its technical drawbacks make it difficult in terms of physical layer. Future works focus on firstly, imposing these different communication topologies into secondary controller of the MTDC system and comparing the performance in terms of resiliency, robustness, and flexibility. Moreover, communication latency will be regarded in next work.

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