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Impact of Grid Forming Power Converters on the Provision of Grid Services through VSC-HVdc Systems

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***Abstract*—High Voltage dc (HVdc) transmission systems have gained increased popularity as a flexible and efficient power transmission option with higher grid controllability. Widespread adoption of HVdc systems for interconnecting power systems and integrating large renewable energy generation facilities such as wind farms, has forced the power system to undergo a transition from a predominantly ac system into a hybrid ac-dc system, specially in the high voltage transmission grid. This paper attempts to provide an overview on the role of Voltage Source Converter based HVdc(VSC-HVdc) systems within the evolving power system as a grid services provider. Special attention is paid to discuss the impact of Grid Forming converter control approach on the provision of such services through VSC-HVdc systems.**

***Index Terms* - grid forming, grid services, hybrid-grid, VSC-HVdc**

I. INTRODUCTION

The power systems around the world is in a transition phase. Synchronous generators in power generation are increasingly replaced by Renewable Energy Sources(RES) interfaced through power electronic converters [1]. The transmission grid which was predominantly based on ac transmission links, is now moving into a hybrid ac-dc grid with increased HVdc transmission capacity installed into the grid [2]. On the other hand there has been an increased tendency to interface large scale industrial loads to the grid through power electronics leading to inverter dominance in all major aspects of the power system from generation to consumption [3]. Notably, within the transmission grid, there has been an increased tendency to opt for Voltage Source Converter(VSC) based HVdc systems which offer various technical advantages compared to classic Line Commuted Converter(LCC) HVdc technology [4].

In order to guarantee the quality, reliability and security of the power system, it requires Grid Services(GS) which can be identified as measures necessary to keep frequency, voltage and load of grid operating equipment within the approved limits, or return them to the normal range after malfunctions [5]. It is notable that there is no universal agreement on this definition, the list of GS or their naming convention. A table outlining different classifications of GS adopted by various system operators and academic community members can be found in [2]. In conventional large scale power systems, the role of providing GS is mainly achieved by employing capabilities of synchronous machines and ac components in the power system [2]. Power system's paradigm shift into a hybrid ac-dc system demands participation of both ac and dc system components in providing GS to the future power grid. This fundamental change in operational architecture comes with a range of challenges and it is important that strategies are proactively developed enabling the coordinated participation of both ac and dc components in providing GS to the power grid [2], [6]. It has been evident that VSC-HVdc systems could offer much more to the evolving power system as a GS provider rather than acting as a mere power transmission infrastructure [7].

This paper attempts to provide an overview on the possibilities offered by VSC-HVdc systems to provide GS within a hybrid ac-dc power grid. A special attention is given to discuss the implications of novel Grid Forming(GFM) control approach in providing such services compared to conventional Grid Following(GFL) control approach. The paper is organized as follows; An introduction to HVdc systems and GFM control approach are provided in Section II and III respectively. An overview on GS provision using VSC-HVdc systems

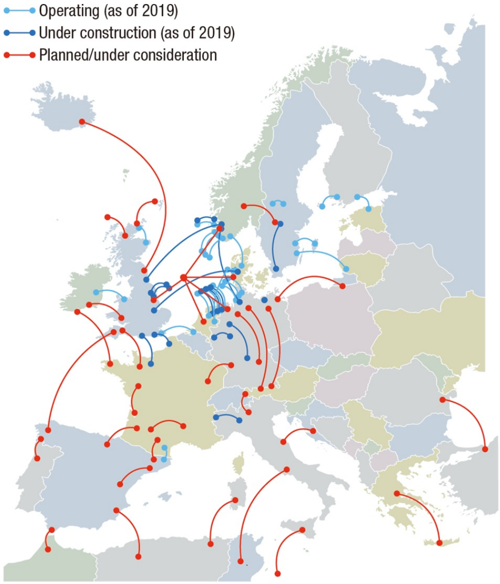


Fig. 1. VSC-HVdc systems in Europe [4]

is given in Section IV, which will be followed by a discussion on implications of GFM control approach in this context in Section V. The conclusions are given in Section VI.

II. HVDC SYSTEMS

Cumulative installed capacity of VSC-HVdc systems that stood below 2.5GW by 2009 (10 years after first such commercial installation), exceeded 20GW by the end of year 2019. The trend is expected to continue in future with an anticipated 35 GW or more of new capacity to be commissioned between 2020 and 2028 [4]. Developments in power electronics, specially advances in multi-level converter technology leading to VSC-HVdc systems of higher capacities up to 1GW, has been instrumental in this development. Europe's existing and planned VSC-HVdc systems are shown in Figure 1 which highlight their prominent role in Europe's future power grid. Similar trends follow in rest of the world.

Some of the key driving factors for increased adoption of HVdc systems include large scale integration of RES which are usually located away from load centers demanding long distance bulk power transfer, cross-regional energy trading (e.g realization of integrated European energy market) and the flexibility offered by HVdc systems to provide additional services to the power system in the view of meeting the rising demand for a reliable power grid [4], [7]. Recently, embedded HVdc systems based on VSC-HVdc technology which connect two nodes within the same synchronous ac network have gained popularity, mainly because of their capabilities to provide additional services to the power grid [8].

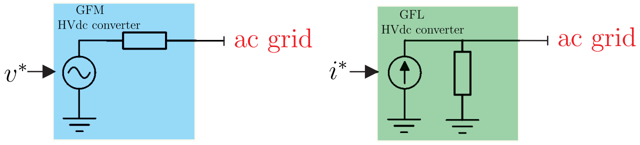
A detailed comparison between LCC and VSC HVdc technologies can be found in [9]. Notably, the ability of VSC-HVdc systems to operate within weak ac grids even without the presence of an ac voltage source, flexibility to control active and reactive power flows independently, and consequently their ability to provide additional services to the connected power grid have made them attractive options compared to LCC-HVdc systems. Focus of this paper in subsequent sections will be on VSC-HVdc systems.

III. GRID FORMING CONTROL APPROACH

Grid Following(GFL) control approach is the well understood and widely adopted control strategy in conventional grid connected power converters. GFL approach essentially requires a dedicated unit (usually a Phase Locked Loop (PLL)) to synchronize with the connected ac grid and follow it for its operation giving rise to the term "*following*". Classic VSC-HVdc converter stations are designed to operate in GFL approach. In this approach, under normal system operation, one of the converter stations in a two terminal HVdc system adopts active power control while the other station operates in dc link voltage control mode. Converters in either side may operate in reactive power control or ac voltage control modes. GS provision in GFL approach based VSC-HVdc systems involve appropriate use of outer control loops to influence active and reactive power references of the converter stations.

Over the last decade, there has been a growing attention on an alternative control approach namely Grid Forming (GFM) control approach within the power electronics and power systems communities. Initially proposed for microgrid applications to behave as an ideal voltage source, which could reproduce a reference voltage for the microgrid in case of islanded operation [10], it is now being investigated as a viable control approach for various converter applications including HVdc systems, renewable energy generations and battery energy storage systems [11], [12]. Recently, commercial applications of the GFM control approach are found. 37MVA/8MWh Dalrymple Battery Energy Storage System built in 2018 in South Australia is the world's first such large scale commercial application [13], [11].

The control philosophy and capabilities of GFM approach are fundamentally different to those of GFL converters. Despite there are discussions in various platforms in Europe (ENTSO-E, Great Britain and Germany)



(a) (b)

Fig. 2. Simplified representation of a VSC-HVdc converter station connected to the ac grid (a) Controlled in GFM approach, (b) Controlled in GFL approach

and rest of the world, until now, there is no finalized standard that provides a definition for the term a "grid forming converter" or "grid forming capability". A large variety of GFM control strategies has been presented in the literature, such as the droop based [14], virtual synchronous machine [15] and virtual oscillator control [16]. The recent article [12], by considering a range of such implementations, has presented a general structure of a converter controlled in GFM approach. In this article, it is shown that state of the art GFM controller implementations can be characterised by having an outer control loop which generates the angle θ, the frequency ω and amplitude E_p of the inner virtual voltage source and an inner control loop that is in charge of all the remaining control actions necessary to generate the modulation signal for the converter's power electronic switches.

A highly simplified representation of a VSC-HVdc converter station connected to the ac grid adapted accordingly from [17] is given in Figure 2. Most importantly, in grid's point of view, a GFM-HVdc converter behaves as a controllable voltage source with low series impedance, whereas a GFL-HVdc converter behaves as a controllable current source with high shunt impedance. Table I summarizes main conceptual differences between GFM and GFL control approaches as identified in [12].

IV. HVDC GRID SERVICES

An overview of capabilities of VSC-HVdc systems in providing GS to the power system is provided in this section considering four significant GS.

A. *Frequency Regulation*

Frequency regulation capabilities of VSC-HVdc systems studied in literature can be classified under two cases: (1)HVdc asynchronous grid interconnection, (2)HVdc offshore Wind Farm interconnection. In the former case, frequency support functions involve exchange of active power between interconnected power system control areas. In [18] and [19], a novel strategy that employs the HVdc system in conjunction with voltage-sensitive ac load control (via controlled reactive power injection) for frequency regulation services has been proposed. This strategy allows possibility to extend frequency regulation function to the embedded HVdc system minimizing the impact on supporting grid's frequency stability.

In several articles (such as [20], [21], [22], [23]), the possibility of variable speed wind turbines to respond to a frequency event in the connected ac grid by exploiting stored energy in its rotor has been discussed. In the case of an offshore Wind Farm connected through an HVdc link, it is necessary to transfer information on onshore grid frequency dynamics to the offshore grid either by means of a dedicated communication link or a communication-less strategy. Widely discussed communication-less approach in this context involves controlling the dc link voltage of the onshore HVdc converter station proportional to onshore grid frequency and subsequently controlling the offshore grid frequency by means of the offshore HVdc converter station based on its dc link voltage [24].

B. *Voltage Regulation*

Control action to maintain the bus voltage levels of the power system within allowable limits is termed as voltage regulation. Other than fulfilling expectations specified in grid codes, voltage regulation helps to minimize losses, improve power transfer capability and increase network stability [7], [8]. Flexibility of controlling reactive power references in VSC-HVdc converter stations independent of their active power flows (adhering to converter ratings) makes VSC-HVdc systems a promising candidate in providing grid voltage support services. Specially, in the view of retirement of coal and nuclear power plants based on synchronous generators that conventionally provided reactive power support to the power system, it is important that capabilities of VSC-HVdc converters are utilized to make up for this deficiency. Embedded VSC-HVdc links integrated to highly meshed ac grids with parallel lines within relatively shorter distances exhibit promising potential in providing reactive power/ voltage regulation services to the power system [8].

C. *Power Oscillation Damping*

In the presence of internal or external disturbances, the power system may experience low frequency oscillations which could be detrimental to its stable and secure operation, unless properly damped [6], [25]. These oscillations can be either inter-area (oscillations between groups

TABLE I
MAIN CONCEPTUAL DIFFERENCES BETWEEN GFM AND GFL CONTROL APPROACHES

Feature	GFL approach	GFM approach
Converter behaviour	Controllable current source with high shunt impedance	Controllable voltage source with low series impedance
Control of active and reactive power injection	Via the control of active and reactive currents	Via the control of phase and magnitude of the inner voltage source
Requirement of a dedicated grid synchronization unit	Required	Not necessary for normal operation.
Grid voltage at the grid connection point(PCC)	Determination of PCC grid phase angle is necessary for proper operation	Converter is capable of providing grid voltage reference to the grid at PCC

of generators interconnected through weak transmission lines) or intra-area (a single generating plant or a small group of generators oscillating against the rest of the power system) oscillations [25]. In conventional power systems, Power Oscillation Damping(POD) is mainly taken care by power system stabilizers and flexible ac transmission system devices such as static VAR compensator and static synchronous compensator [26].

The fact that HVdc systems usually bridge large distances makes them to have strong influence on the dominant power system modes, thus making them excellent choices for POD. It is possible to achieve POD with active and reactive power modulation [26]. POD capabilities of VSC-HVdc systems have been explored in literature mostly focussing on inter-area oscillation damping based on point-to-point HVdc systems. Possibility of offshore wind farms integrated via HVdc systems and multiterminal dc systems in providing power oscillation damping to the connected power system has also been studied (e.g. in [27], [28]). A detailed review in this context can be found in [29]. The majority of early works deal with GFL control approach while recent publications such as [25] (based on synchronverter) and [30] (based on virtual synchronous machine) have indicated the possibility of POD based on GFM control approaches.

D. Black Start Services

The process of restoring the portion of a power grid that has been affected by a power outage to its normal operating conditions is termed as black start [31]. It is a complex process that involves restarting generating units, energizing transmission system elements, and gradually restoring the loads [32]. In conventional power systems, black start process is usually initiated by gas turbines or pumped storage hydro power plants which are based on synchronous generators [33]. Reducing system inertia and increased share of intermittent RES penetration within the power systems has made it increasingly vulnerable to events leading to blackouts.

Black start capability of VSC-HVdc systems has already been validated in several field tests [34], [35]. VSC-HVdc systems could operate within a dead network [31] under zero or very low power transfers with independent control of active and reactive power enabling them to act similar to a synchronous generator forming a grid during the restoration process [34]. HVdc link could, in fact, act as a dynamic controllable active and reactive power reserve thus reducing the risk of uncontrolled power flows leading to system instability during the restoration process.

Capability of VSC-HVdc systems connecting asynchronous grids and Wind Power Plants(WPP) has widely been discussed in literature. In this case, the converter station in active power grid adopts dc link voltage control and reactive power (or ac voltage) control whereas the converter station in the dead power system forms the grid by gradually ramping up the grid voltage [36]. In [34] and [35], field test results based on Estlink VSC-HVdc link conforming the possibility of a VSC-HVdc system to successfully black start a dead grid have been presented.

Several studies (such as [33], [37]) have investigated the possibility of providing black start restoration support to the onshore power grid via VSC-HVdc connected offshore WPPs. In these studies the offshore grid is first formed by the WPP. Offshore VSC-HVdc converter operates in GFL mode providing necessary reactive power support to the offshore grid. Subsequently, onshore grid is formed by the onshore VSC-HVdc converter station similar to an asynchronous HVdc connection case mentioned before. Recent article [38], through simulation studies, makes an interesting comparison between four GFM control approaches in providing black start services using HVdc connected WPP. The study, however, neglects WF's rotor and dc link dynamics.

V. DISCUSSION

In the view of power system's paradigm shift with increasing number of synchronous generators being replaced with inverter based generation sources and increased penetration of inverter based power sources and HVdc links into the transmission infrastructure, provision of GS to the power system need to be rethought. Capabilities of VSC-HVdc systems in the provision of various grid services has been widely studied in literature and commercial applications of VSC-HVdc systems as a GS provider are already in place. It can be noted that the early control strategies developed to control VSC-HVdc systems are mainly based on well known GFL control strategy. Recently, there has been an increased interest within the research community and the system operators to understand the possibilities offered by GFM control approach as a key enabler of the paradigm shift in the power system. Even though some of the research in this context are not directly related to HVdc systems, outcomes of such studies are directly applicable to VSC-HVdc systems considering the fact that in power system's point of view, the interaction of an HVdc system has no difference to any other inverter based power source. The following section provides a discussion on implications of GFM control approach in providing various GS to the power system via VSC-HVdc systems.

One of the appealing features of an HVdc converter station controlled in GFM approach is its ability to provide comparable behaviour to a conventional synchronous generator in terms of forming the grid. Converters controlled in GFL strategy do not inherently provide grid forming capability or services provided by synchronous generators [48]. The behaviour of a GFM-HVdc converter station that approximates to a voltage source behind an impedance [12], much similar to that of a synchronous generator [40], could lead to superior performance in the form of an instantaneous response to a disturbance in the grid. This can be specially beneficial in providing frequency and voltage regulation services. An HVdc converter station controlled in GFL approach, first needs to estimate the grid event leading to voltage or frequency deviation (usually with the use of a PLL), process the measurement, calculate the reference currents and subsequently react to the event by controlling its currents. A GFM-HVdc converter station could, instead exchange active and reactive power almost instantaneously in the case of a frequency or voltage event in the grid [1], [10] providing superior regulation service to the grid. In [41], the authors proposed synchronverter based GFM control approach for HVdc converter to emulate a classic synchronous generator. In this study, authors have shown that it is possible to achieve better dynamic performance and improved stability margin compared to conventional GFL control approach. In [39] and [40], it has been shown that a GFM converter could act as a source damping to the power system frequency dynamics compared to GFL converters with frequency support functions under low inertia or high inverter penetration scenarios. Furthermore a GFM-HVdc station would not suffer from the negative impacts of PLLs on its performance within weak ac system connections, as reported in [10].

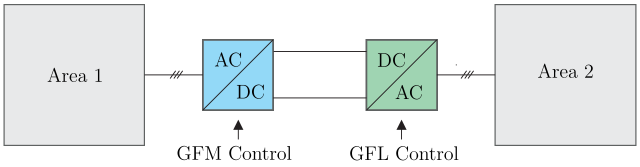


Fig. 3. Simulated power system

A GFM-HVdc converter station's reaction to a disturbance in a low inertia power system was tested in a simulation study. As shown in Figure 3, the GFM-HVdc converter is connected to power system Area 1 which is modelled as a low inertia power system with an inertia constant of 2s. Initial active power reference of the HVdc link is set to 0p.u. A large load of 0.5p.u is connected to Area 1 at 5s and its effects on frequency dynamics of Area 1 are studied considering the presence and absence of this HVdc link. Simulation results are shown in Figure 4. It is clearly seen in Figure 4(a) that the action of the GFM-HVdc converter station reduces the rate of change of frequency and improves frequency nadir of the power system. Interestingly, as evident in the zoomed view of frequency of Area 1 measured by the PLL (in Figure 4(c)) and zoomed view of active power contribution from GFM-HVdc converter (in Figure 4(d)), the reaction of GFM-HVdc converter takes place almost instantaneously even before the PLL detects a frequency deviation. Note that the PLL is used only for demonstration purposes. Furthermore, no primary frequency regulation function is expected from the HVdc link in this analysis.

Operational behaviour of a synchronous generator is generally dictated by its physical construction. However, the behaviour of a GFM-HVdc converter station can be flexibility altered by means of the control system [48]. For instance, a GFM-HVdc converter station may raise

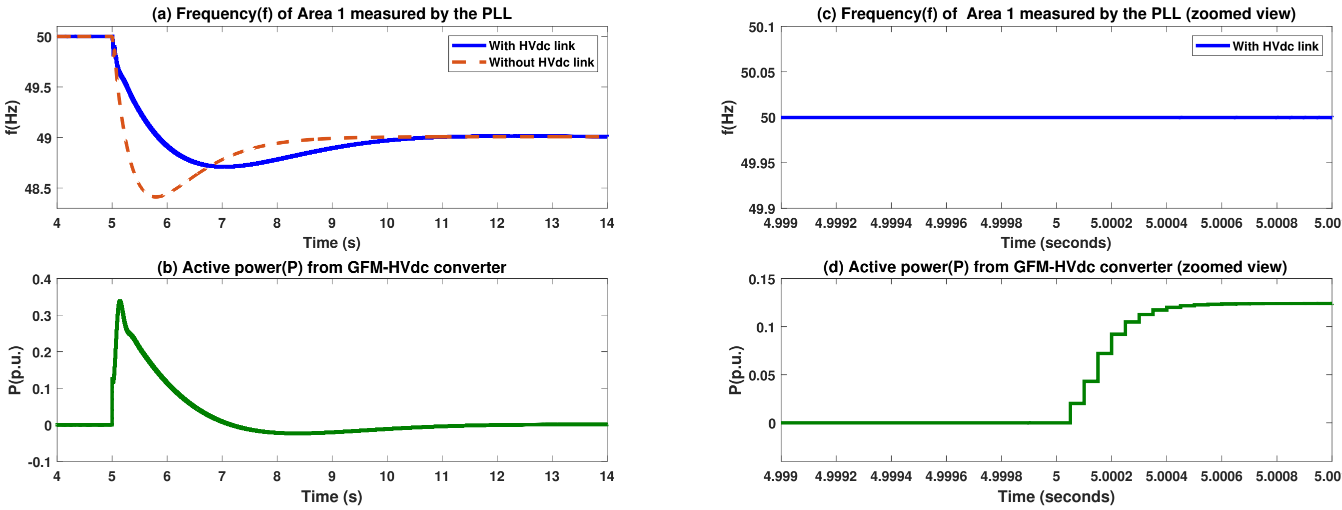


Fig. 4. Simulation results: contribution of a GFM-HVdc converter station in stabilizing a low inertia power system. (a)Frequency of Area 1 measured by the PLL, with and without HVdc link. (b)Active power contribution from GFM-HVdc converter to Area 1. (c)Zoomed view of the frequency of Area 1 measured by the PLL. (d)Zoomed view of Active power contribution from GFM-HVdc converter to Area 1

its synthetic inertia contribution during the black start sequence[11] so that the system could better withstand load imbalances. GFM based approaches proposed for frequency regulation (such as [41], [42]) and for POD (such as [41]) also benefit from adaptive gains. However, implications of such adjustments on overall stability of the system, requires careful consideration.

High power ratings associated with HVdc links imply that a single HVdc converter station operating in GFM approach could provide equivalent influence on the grid comparable to a conventional large synchronous generation facility in providing GS [48]. In the view of reducing share of synchronous generators within the power system, promising potential of GFM controlled HVdc converter stations in improving grid short circuit level is under discussion in several platforms [47].

However, it should be noted that applications of GFM control approach for HVdc systems would come with a range of challenges such as over-current limitation and maintaining transient stability of the converter stations [10], [39], [48] which are some of the inherent challenges associated with GFM control approach. Solutions to some of these challenges have already been investigated (such as protection of GFM converters in [44], Fault Ride Through in [45]), but without specific reference to HVdc technology. It is also noteworthy that an HVdc link itself is not an energy source [26] (except for limited stored energy in HVdc system's dc link). Operational challenges associated with GFM controlled HVdc converter stations in terms of sourcing required energy while maintaining stability of the interconnected power system areas need to be investigated. Furthermore, interactions between GFM-HVdc converter stations and the grid need to be better understood. Majority of the existing studies in this regard are based on highly simplified assumptions which are questionable within changing power system architecture.

A comprehensive list of open research questions related to applications of GFM control approach in grid connected power converters can be found in [46] . Generally, even though GFM control approach is widely discussed in literature, there is a lack of studies that specifically focus on its direct applications to HVdc systems. A summary outlining opportunities and challenges of GFM control approach in providing GS though VSC-HVdc systems can be found in Table II.

VI. Conclusion

The role of VSC-HVdc systems within the changing power system architecture beyond a mere power transmission infrastructure has been widely accepted among the system operators and the research community. VSC-HVdc technology has found widespread adoption within the modern power systems subsequently leading to a hybrid ac-dc power system. Capability of VSC-HVdc systems to act as a grid services provider has gained increasing interest specially in the view of reducing share of synchronous generators and ac components of the power system that conventionally offered such services. Early strategies developed to control VSC-HVdc systems and exploit their potential as a grid services

TABLE II
OPPORTUNITIES AND CHALLENGES OF GFM APPROACH IN PROVIDING GRID SERVICES

Grid service	Opportunities	Challenges
Frequency regulation	Almost instantaneous reaction ([1], [10]) Act as a source of damping to- frequency dynamics ([39], [40]) Possibility operate within a weak grid No instability issues due to PLL ([10]) Faster/ controllable dynamics compared to - synchronous generators ([41], [42], [43])	Protection of HVdc converters [44] Limitation of converter currents [12] Fault Ride Through [45] Maintaining transient stability [12] Lack of understanding on interactions - between the changing power system [46]
Voltage regulation	Almost instantaneous reaction ([1], [10], [45]) Improvement in grid short circuit level ([47])	
Power oscillation damping	No instability issues due to PLL ([10]) Flexible damping capabilities with - adaptive gains ([25], [30])	
Black start	Grid forming capability similar to a - synchronous generator ([34], [35]) High level of flexibility and faster dynamics ([38])	

provider have been based on well known GFL control approach, whereas there has been an increased interest on applications of GFM control approach in this context. The review indicates that VSC-HVdc converter stations controlled in GFM approach could provide various possibilities in resolving challenges within the evolving power system mainly because of their inherent capability to behave similar to synchronous generators in certain aspects but with faster dynamics and controllability. Nevertheless, inherent challenges associated with GFM control approach such as protection and transient stability of HVdc converter stations and their interactions with the changing power system require further investigations to fully exploit such benefits.

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