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Interarea Oscillation Damping Control Using High Voltage DC Transmission: a Survey

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***Abstract*—High-voltage, direct current (HVDC) transmission lines are increasingly being installed in power systems around the world, and this trend is expected to continue with advancements in power electronics technology. These advancements are also bringing multi-terminal direct current (MTDC) systems closer to practical application. In addition, the continued deployment of phasor measurement units (PMUs) makes dynamic information about a large power system readily available for highly controllable components, such as HVDC lines. All these trends have increased the appeal of modulating HVDC lines and MTDC systems to provide grid services in addition to bulk power transfers. This paper provides a literature survey of HVDC and MTDC damping controllers for interarea oscillations in large interconnected power systems. The literature shows a progression from theoretical research to practical applications. There are already practical implementations of HVDC modulation for lines in point-to-point configuration, although the modulation of MTDC systems is still in the research stage. As a conclusion, this paper identifies and summarizes open questions that remain to be tackled by researchers and engineers.**

***Index Terms*-- HVDC transmission, power system stability, power system control.**

I. Introduction

THE first high-voltage, direct current (HVDC) system in practical use is generally reckoned to be the submarine line from the mainland of Sweden to the island of Gotland, installed in 1954 [1], [2]. Already at the time, the question of stability when a HVDC system was inside an ac system was being investigated [3], [4]. Power system stability was becoming a research topic of interest in the western US [5], [6]. As the interest in HVDC grew, the possibility of using the controllability of HVDC to add damping to the oscillatory motions seen in some ac power systems was investigated [7]. At about the same time, the idea of controlling the exciters of generators for the same purpose was also investigated in [8] and [9].

Since then, active damping has been extensively investigated to improve the dynamic response of power systems to interarea oscillations, which in turn would improve system reliability [10]. A well-known damping controller is the power system stabilizer (PSS). However, PSSs, which are based on local information, have limited effect on interarea oscillations unless they are carefully coordinated [11].

Although less common than PSSs, power oscillation damper controller [12] in flexible ac transmission systems (FACTS) using local measurements have been used. This type of controllers have been recently applied with utilization of wide-area information [13].

The availability of wide-area information from phasor measurement units (PMUs) offers the promise of greatly improved damping of interarea oscillations. This promise is reinforced by the clear trend of increased installations of HVDC lines in power systems around the world as reported in [14] and [15], and illustrated in Section V of this paper. Motivated by this strong trend for installing more HVDC, this paper surveys proposals and prototypes for controlling HVDC lines and multi-terminal direct current (MTDC) systems. Although the use of HVDC for damping of torsional vibration resonance [16], [17], [18] and sharing primary frequency response between two systems [19], [20], [21], [22] has also been reported, those are not the focus of this survey paper. This paper focuses on interarea oscillations.

The rest of the paper is organized as follows. Section II gives background information on the need to provide oscillation damping and the use of HVDC for bulk power transfers and for additional grid services. Section III surveys literature on modulation of point-to-point HVDC lines. Section IV surveys proposals for MTDC systems. Section V surveys historical trends for installation of HVDC lines and mentions examples of HVDC expansion plans. Finally, Section VI provides conclusions and a summary of questions identified in this survey.

II. Background

A. Need for oscillation damping control in power systems

Introductory textbooks teach that the frequency of the power system is constant, and the power flow is a function of the angles and the voltages. However, the reality is slightly

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different. In fact, any given generator may oscillate around the steady position that the simplified analysis gives, and groups of generators can move together against other groups of generators in the power system. Such motions are electromechanical in nature, and have characteristic frequencies that are largely determined by the inertia of the rotating masses of alternators and turbines, and the network topology of the power system.

As a result of various groups of generators oscillating against each other, several characteristic frequencies can be identified in a large system, such as the Western Electricity Coordinating Council (WECC). Usually, these oscillations are small and fairly well damped. Conceptually, the matter is amenable to the ideas of small-signal stability, where the damping term is readily identified. Interarea oscillations, which may take place over distances of hundreds or even thousands of kilometers, can be viewed in terms of oscillations with corresponding frequency and damping characteristics.

Sometimes the damping becomes negative, and system oscillations grow. Such a situation can occur following a switching event in which one or more lines are lost. In this case, the system state may evolve from an initial deviation from steady state, and instability can result. The infamous system breakup across the west coast of North America in 1996 can in part be attributed to undamped oscillations [23].

Keeping the damping positive is a goal of PSSs and of the HVDC modulation we consider in this paper.

B. HVDC transmission

The kind of converter used for the Gotland scheme mentioned above was based on mercury-arc switching devices. In these devices, the current between the anode and the cathode was initiated in a plasma of mercury vapor by a pulse from a grid electrode. Once initiated, the current continued as long as the anode was positive with respect to the cathode, whether or not the grid pulse was removed. Switching therefore took place at the power frequency. During conduction, the current was constant, and commutated from one valve to another via a temporary phase-to-phase short circuit. This was the kind of converter that existed in 1960 when the first English-language text on HVDC was published [24]. Exactly the same switching properties were in effect when semiconductors replaced mercury-arc devices beginning in 1962 [25]. These converters are now known as line-commutated converters (LCCs).

A major change in converter technology was made possible with the invention of the insulated-gate bipolar transistor (IGBT) around 1980 [26]. The current through IGBT devices can be stopped even if the anode is positive with respect to the cathode. Converters based on this technology have an additional degree of freedom in their operation: it is possible to control not only when during the cycle the valve conducts, but also when it stops. These converters are known as voltage-sourced converters (VSCs).

Early versions of the VSC used a kind of pulse-width modulation to approximate the ac waveform, switching much faster than the power frequency. Their losses were therefore not low, as some loss is associated with every switching operation. A revised converter design allowed the switching of stacks of IGBTs in series, with groups switching at the power frequency [27]. These converters, known as modular multilevel converters, allow losses to be reduced and efficiencies to be increased to the point that they are competitive with LCCs. Their control flexibility allows them to be used to create HVDC networks [28].

C. HVDC lines used for additional services other than bulk power transfers

It has been recognized from the beginning that HVDC can offer some advantages over ac. Under certain circumstances, the economic benefit is significant: underwater cables, for example, were early applications of HVDC. Other installations delivered power to places where the fault level was high, and the use of ac would have meant upgrading the local circuit breakers. So while the main reason to use HVDC may be to transfer power economically over some path, it is not unknown to take additional advantage of their controllability. In particular, stability improvement has already been one of these options for half a century.

III. CONTROL USING HVDC POINT-TO-POINT LINES

This section surveys control strategies proposed for HVDC point-to-point lines to provide damping control to ac interconnections. The concept has been studied over at least the last 40 years. Damping of this kind was not mentioned in the foundational texts on HVDC. Adamson and Hingorani [24] mention damping only in the context of the effect of a sudden rise in voltage when a converter is deblocked, for example. The topic is explored in somewhat more depth in [29]. But again there is no mention of system-level damping: the concern is overvoltages on deblocking. This book mentions the matter of resonance of the dc-side connection, for example, the dc line cross-channel link, the cable under the English Channel. The later book by Kimbark [30]) covers line resonance in great detail. The book discusses power system stability (a subject of great interest to Kimbark, who had published a book on the topic in 1948 [31]), but does not include mention of using the dc line for damping. Kimbark was likely aware of the work in Philadelphia [7] [32] but the work on stability control going on in his company at the time was focused elsewhere [5] [6].

System damping management has recently been brought back to the attention of the research community because of the opportunities presented by PMUs and the renewed interest in installing HVDC transmission. A brief summary of the survey of this section is in Table I, second row, and can be quickly compared to the survey summary for MTDC from Section IV (Table I, third row).

A. Early development and practical implementations

The control method in the early stage was mostly based on modulating the dc power flow in proportion to the frequency difference between the two ends of the line. Dougherty and Hillesland [7] verified that the very rapid control of power possible on HVDC transmission can provide strong damping to disturbances within the power system. Cresap and Mittelstadt [33] designed a control algorithm for small-signal modulation of HVDC lines. The control signals on the rectifier side were based on the rate of change of power on the ac interties. The signals required taking derivatives, which was a noise-prone process. This scheme was proposed for the HVDC Pacific dc Intertie (PDCI) in the WECC. In Cresap *et al.* [34], test results from a prototype damping control system to modulate power flow on the PDCI were reported. The original design utilized the real power flow on the California-Oregon Intertie as the feedback signal. Even though this method provided damping to low frequency modes of oscillation, further analysis determined that the local ac power flow feedback signal, had a transfer-function zero that limited the gain of the controller and caused oscillations at higher frequencies to worsen [35]. Martin *et al.* [36] verified that the modulation controls on another HVDC line in the WECC system, the Intermountain Power Project (IPP), could significantly improve the performance and damp interarea oscillations.

Grund *et al.* [37] designed a coordinated control of an active and reactive power HVDC modulation for an ac/dc transmission system to increase power transfers limited by dynamic stability. The control was achieved by modulating the rectifier direct current or power and the inverter dc voltage. Szechtman *et al.* [38] presented a constant reactive current control method that enabled the dc link to show an effective gain in transmitted power by a small reduction in the direct voltage, allowing full use of valve current capability.

Badran and Choudhry [39] proposed a linear quadratic regulator-based optimal modulation controller for a multi-area ac/dc system to assign the modes corresponding to electromechanical oscillations. The results indicated that the proposed technique improved both the calculation time and the performance of system damping by active and reactive power modulation. Hao [40] designed a modulation controller for the Tianshenqiao to Guangdong HVDC transmission to damp the power oscillations of the parallel ac line. It was found that the HVDC power modulation could increase the stability of ac systems for highly loaded ac lines or single pole blocking situations. Smed and Andersson [41] analyzed the active and reactive power modulation of HVDC links regarding interarea oscillations. The results showed that active power modulation was most efficient when applied at a short distance from one of the swinging machines, and reactive power modulation was most efficient when the power flow direction was well defined and the modulation was made at a point close to the midpoint between the swinging machines. Kundur [42] provides an illustrative example of supplementary control for HVDC to stabilize a test power system. Rogers [43] analyzed three different damping control schemes applied to the Kundur two-area model [42]. The methods employed were dynamic feedback informed by the residues of the system transfer function [44], robust control based on H_∞ optimal control [45], and control using μ-synthesis methods [46]. Comparative analysis of the three control schemes showed that the minimum-phase control design obtained from μ-synthesis methods produced superior damping performance.

Mao *et al.* [47] described a comprehensive small-signal analysis for the China Southern Power Grid in 2005 and explored the coordination and parameter optimization of selected PSSs and HVDC controllers for improved interarea oscillation damping. Teeuwsen and Rössel [48] described the modulation of the BritNed HVDC Interconnector, which was a bipolar power transmission project establishing the first HVDC link between Great Britain and the Netherlands. Power-system stability analysis of the British and the Dutch power systems showed that fast modulation of the HVDC line could improve the transient stability of the interconnected system.

B. Developments that use wide-area measurements

With the development of wide-area measurement technology, PMU-based control methods could offer promising solutions for interarea oscillation damping in a large system. Peng *et al.* [49] presented use of PMU measurements as input to a continuous feedback control system in a real bulk power grid in China. Closed-loop field testing of a wide-area damping control (WADC) system showed that WADC offered significant damping of interarea modes. Trudnowski *et al.* [35] evaluated PDCI damping control in the WECC system, concluding that relative frequency feedback was a robust signal to be used for modulation. The study also concluded that modulation of ±100 MW to ±200 MW can provide significant damping.

Pierre *et al.* [50] and Schoenwald *et al.* [10], implemented a prototype that used real-time PMU feedback to modulate the real power over the HVDC; this is the implementation of the proposal theoretically outlined in [35]. The prototype implemented a control logic based on frequency difference. The frequency difference was obtained from electrical angle difference from PMUs, and this signal was passed through a derivative filter.[1] A similar controller was used by Neely *et al.* [51] to study a combination of HVDC and energy storage modulation.

Testing experience from HVDC damping controllers in the China Southern Grid are described in Lu *et al.* [52]. Other wide-area damping controllers that use PMU measurements have been developed and tested—for example, in Norway [13], where the actuator is a thyristor-controlled reactor static var compensator.

C. Consideration of communication delays

Communication delay could be a serious challenge to WADC. Schoenwald *et al.* [10], considered communication

[1] The reader might wonder why the process retained the idea of taking a derivative, when the straightforward subtraction of the frequency signals from two PMUs should give the same information. The answer seems to lie in the manufacturer-to-manufacturer variability of the delay in processing the frequency signal inside the PMU. Because the delay (which seems to be caused by a low-pass filter in the signal path) is evidently not fixed by the applicable standard, several workers in the field have elected to discard the frequency reports from the PMU and calculate a value by differentiating the reported angle signal.

delays in prototype implementation of HVDC modulation.

Neely *et al.* [53] proposed a controller design based on frequency difference but applied to energy storage. The control design provided allowable ranges of gains and time delay parameters ensuring the Nyquist stability criterion is met, in a small power system model. In this work, the damping was studied for the north-south oscillation mode, which was aligned with the PDCI. He *et al.* [54] designed an experimental system to investigate the effect of time delay on the supplementary damping control of HVDC. For the specific Gao-Zhao supplementary damping control design in the China Southern Grid, the system could remain stable under a delay of 220 ms or even more.

Roberson and O'Brien [55] proposed a compensator designed with a loop shaping method. The design avoided bandwidth constraints caused by limitations in time delay among other factors.

Hadjikypris *et al.* [56] considered time delays introduced by communication infrastructure in a control for coordination between HVDC and FACTS devices. It was concluded that the delay did not affect the damping effect of the proposed coordinated control.

D. Proposals for advanced control strategies

Advanced control strategies such as model predictive control (MPC) have recently been proposed. In [57], the MPC-based control was applied on an LCC-HVDC link and its performance was compared with linear quadratic Gaussian (LQG) controllers. The MPC was found superior. The main feature of this type of control was its ability to cope with hard constraints on inputs, outputs, and states. The MPC could address actuator limitations and it enabled operation closer to the system constraints, which resulted in faster system response. Fuchs and Morari [58] proposed a global MPC scheme to provide damping modulation with four HVDC links. The MPC scheme was able to consider constraints and expected future behavior of system. The system used the European Network of Transmission System Operators for Electricity (ENTSO-E) test system (74 buses with generation and load, 131 ac lines) with four HVDC lines. Frequency difference of two remote regions was selected as the global input signal.

Roberson and O'Brien [55] proposed a compensator designed with a loop shaping method providing performance and noise response improvement with guaranteed stability in saturation. The method could place poles and zeros to shape the loop transmission that realized the desired feedback subject to the bandwidth. The authors stated that this design could overcome some of the limitations of using a frequency difference controller, such as the ones proposed in [35] and [50], avoiding bandwidth constraints caused by limitations in time delay, sensor and actuator dynamics, and the fidelity of the linearized model at high frequency.

Zeni *et al.* [59] proposed providing oscillation damping from VSC-based HVDC connecting offshore wind power plants, by modulating their active and reactive power injections. Fan *et al.* [60] studied the use of wind generation that modulates the real power of a wind generator's doubly fed induction generator and HVDC rectifier power modulation to damp interarea oscillations. Pipelzadeh *et al.* [61] presented a coordinated control method of an offshore wind farm and onshore HVDC converter to damp the interarea power oscillations. The paper showed that the coordinated control could provide effective damping, avoiding problems with undesirable voltage variations or inadequate damping by using only either the wind farm or the HVDC converter. Pipelzadeh *et al.* [62] also presented a case study of using HVDC to damp power oscillation on the Australian system. A multivariable controller, which uses wide-area signals, was proposed to modulate HVDC power order. The same authors also showed that a decentralized controller could overcome the challenge of fast communication of control signals required for a centralized control scheme [63]. In essence, they demonstrate multiple single-input, single-output (SISO) control acting as one multiple-input, multiple output (MIMO) control.

Distributed controllers using various flexible ac transmission system (FACTS) devices and HVDC controllers have been studied to provide good interarea oscillation damping capabilities. Li *et al.* [64] presented a coordinated control approach for HVDC and FACTS devices based on robust control theory. Static var compensator (SVC) and thyristor-controlled series compensation (TCSC) were used with HVDC controllers to stabilize multiple interarea oscillation modes, and the proposed control approach provides good robustness under various operating conditions. Li *et al.* also proposed a hybrid method to assess and select suitable control inputs for the control of HVDC and FACTS devices [65]. A preselection process and relative gain array calculation method were proposed to preselect input signal candidates from large numbers of wide-area and local signals, and to determine the optimal control pairs. The work by Li *et al.* is also presented in more detail in a text book [66]. Hadjikypris *et al.* [56] also proposed to use TCSC and SVC incorporated with HVDC to damp the interarea oscillations based on LQG optimal control theory. The time delays introduced by communication infrastructure were also considered and it was concluded that the delay did not affect the damping effect of the proposed coordinated control of HVDC and FACTS devices. Shi and Liu [67] proposed a low frequency oscillation damping method using HVDC active power modulation and static reactive compensation device (STATCOM) voltage regulation. The reactive power and voltage control of STATCOM mitigated the adverse effects of direct voltage changes during HVDC modulation.

Preece *et al.* [68], [69] implemented a modal linear quadratic Gaussian controller in centralized and decentralized versions to a set of VSC-HVDC links. The performance of the controllers was evaluated using the proposed robust probabilistic methodology, incorporating outages of several pieces of equipment.

Harnefors *et al.* [70] studied the effect of fast HVDC primary frequency control on interarea oscillations. Through theory, analysis, and simulation, the authors showed that

HVDC primary frequency control never decreased the modal damping for the system under consideration.

Adaptive supplementary damping controllers for HVDC were also studied in [71]. Shen *et al.* [71] proposed an adaptive supplementary damping controller for VSC-HVDC, using goal representation heuristic dynamic programming (GrHDP). Ahmad and Khan [72] proposed an adaptive feedback-linearization control strategy to damp interarea oscillations through an HVDC link. The control scheme was based on real-time optimized neuro-fuzzy identification of system dynamics using the conjugate gradient algorithm.

IV. Control using multi-terminal HVDC networks

In Section III, we surveyed the existing literature on controlling point-to-point HVDC lines to damp interarea oscillations. In this section, we focus on literature about multi-terminal dc (MTDC) networks. In the case of MTDC networks, all the development is at a research stage, because there are only two MTDC projects in operation in China [73], [74]. The projects in China were only preceded by two 3-terminal radial lines: Italy–Corsica–Sardinia [75] and Quebec – New England Transmission [76].

MTDC networks have potentially more controllability and flexibility than point-to-point HVDC [28], and therefore could potentially provide enhanced interarea oscillation damping to large ac interconnections. A brief summary of the survey of this section is found in Table I, third row, and can be quickly compared to the survey summary for point-to-point HVDC from Section III (Table I, second row).

A. Early research and development

HVDC networks and coordinated control of several HVDC assets introduced an opportunity to improve system damping. The problem was studied in the past [32], [77] for HVDC based on LCCs. Zaborszky *et al.* [77] proposed to use the observation decoupled reference vector to design an online stabilization scheme for large ac-MTDC systems. Stabilization considering HVDC networks was studied for small systems by Rahman and Dash [78]. Chan and Athans [79] applied robustness margins using an MTDC controller.

Lefebvre *et al.* [80] proposed a new decentralized power modulation scheme for MTDC systems, where only local output variables were used for feedback structure. Eigenvalue assignment techniques were used to damp specific modes without affecting the remaining system eigenvalues.

Carroll and Ong [81] proposed a centralized coordinated modulation of MTDC systems, based on a fast online dc power flow solution. The proposed controller could use the overload capacity of converters. Choudhry and Carroll [82] proposed coordinated active and reactive power modulation for both centralized and decentralized MTDC modulation, for enhanced performance.

Lee *et al.* [83] studied active and reactive power modulation of MTDC networks in the southwestern US, for transient stability and system damping enhancements.

Hamzei-Nejad and Ong [84] studied the feasibility of online coordination of the MTDC system for dynamically controlling the ac power flows, which helped damp oscillations.

B. Recent research and development

The early research and development in MTDC control took place in the 1980s. Recent power electronics technology development, and in particular of modular multilevel converter (MMC)-VSC, has brought MTDC systems closer to practical application. This technology advancement has been accompanied by more recent research and development on the control of MTDC systems.

Resende *et al.* [85] proposed simultaneous tuning of classical PSSs in onshore VSC stations to provide damping to combined ac-MTDC systems of large offshore wind farms connected to an ac system.

Agnihotri *et al.* [86] proposed a robust wide-area damping controller for MTDC systems, using a limited set of remote signals directly communicated to the dc links. The controller design was robust to partial or complete loss of communication, changes in operating points and topology, and communications delays. Frequency difference between ac terminals was used as feedback signals.

Eriksson [87] analyzed the control structure of the MTDC system and proposed a scheme to maximize the relative controllability without communication among dc terminals. The paper concluded that MTDC control direction was interrelated with active power modulation, unlike what happens in point-to-point HVDC control where only phase compensation was enough for maximal damping. The proposed method uses direct voltage feedback-loop shaping to modulate power in one terminal and let other terminals react to direct voltage changes.

Banerjee and Chaudhuri [88] proposed a robust damping control for ac-MTDC systems using the H_∞ mixed-sensitivity method. A linear matrix inequality framework was used to design a damping controller that incorporates weighing filters for disturbance rejection and control energy minimization. Banerjee *et al.* [89] continued with the work on [88] including disturbance rejection into control design by introducing an explicitly modeled disturbance plant. They have also included a multiple input multiple output control design.

Du *et al.* [90] studied dynamic interactions between an MTDC network and an ac power system. The study revealed a special condition where open-loop modal coupling resulted in degradation of small-signal stability of the MTDC/ac system. The condition occurred when a complex pole of the open-loop MTDC subsystem was close to an electromechanical oscillation mode of concern for the open-loop ac subsystem.

Harnefors *et al.* [91] provide analytical results for active power modulation of a four-terminal MTDC system for interarea damping on an idealized two-machine system, and verified them in a larger system. The results showed that pairing of two MTDC terminals usually provides the best damping performance.

Preece and Milanovic [92] proposed a robust probabilistic collocation method for tuning an MTDC system for active power modulation. The method provided robust probabilistic tuning without the need for large numbers of full system linearizations, it was computationally more efficient, and the tuning was more robust than with a Monte Carlo approach.

TABLE I
Summary of Survey for Point-to-Point HVDC Lines and MTDC Configurations

HVDC type	Control signals	Modulated signal	Control design	Communica-tion delays	Coordination
Point-to-point HVDC lines - LCC - VSC	- Frequency difference [35], [50], [10], [35] - Rate of change of power on ac lines [33] - Real power flow on ac lines [34], [35]	- Direct current [37], - DC Power [34] - Direct voltage [38] - AC side active and reactive power [41], [59]	- H infinity [43], [45], [46] - Residues of system transfer function [43], [44] - μ-synthesis [43], [46] - Model predictive control [57], [58] - Linear quadratic Gaussian (LQG) [39], [68], [69] - Loop shaping method [55] - Robust probabilistic methodology for evaluation [68], [69] - Goal representation heuristic dynamic programing [71] - Adaptive linearization, neuro-fuzzy identification [72]	- Studied in [10], [53], [54], [55], [56]	- With storage [51] - With FACTS [13], [64], [65], [56], [67] - With PSS [47] - With wind generation [59], [60], [61]
MTDC - LCC - VSC	- Frequency difference [86], [85] - Active power flow in selected ac lines [78] - Synchronous machines speeds [78] - Combination of direct voltage and frequency [90] - Direct voltage feedback loop shaping; other terminals react to direct voltage changes [87]	- Active power injections [84] - Active and reactive power [83]	- Observation decoupling reference vector [77] - Robustness margins [79] - Decentralized [80], [82] or centralized [81], [82] - Eigenvalue assignment [80] - Simultaneous tuning with PSSs [85] - Feedback loop shaping [87] - H infinity mixed sensitivity [88], [89] - Linear matrix inequality [88], [89] - Weighing filters for disturbance rejection [88], [89] - Control energy minimization [88], [89] - Open-loop modal coupling caused stability degradation [90] - Robust probabilistic collocation method [92] - Modified LQG [92]	- Studied in [86]	- With PSS [85] - With wind generation [85]

V. Historical Trends and Potential for Future Use of HVDC for Oscillation Damping

This section reviews historical trends of installation of HVDC lines around the world and mentions some examples of proposed new HVDC lines.

A. Historical installation of HVDC systems

A list of worldwide HVDC systems by technology, year of commitment, and upgrades is compiled in [14] and [15]. The early HVDC transmission technologies were based on dc generators, as single machine and Thury configurations. Early technologies were followed by mercury-arc valves and the current thyristor and IGBT technologies [93]. Fig. 1 shows the evolution of the historical installation of these technologies from 1882 to 2017, including early technologies based on dc generators (single machine and Thury), and also displaying early prototypes of mercury-arc technologies before the HVDC submarine line implementation in Gotland, Sweden in 1954. The figure shows that growth of installation of HVDC in the last two decades has been significant.

B. Examples of HVDC expansion plans

There are various plans around the world for installing additional HVDC lines embedded in existing large, mostly ac, power system interconnections. In Europe, 31 HVDC lines have been installed to date [94], mostly undersea HVDC cables, and there are various plans for HVDC overlays and HVDC network in the North Sea [94], [95]. China has seen significant recent growth in HVDC, with more than 15 new HVDC lines built in the last five years [14], and concepts for northeast Asia regional grid [96] and global energy interconnections [97] have been proposed. Brazil has recently added the longest HVDC transmission corridor in the world [98].

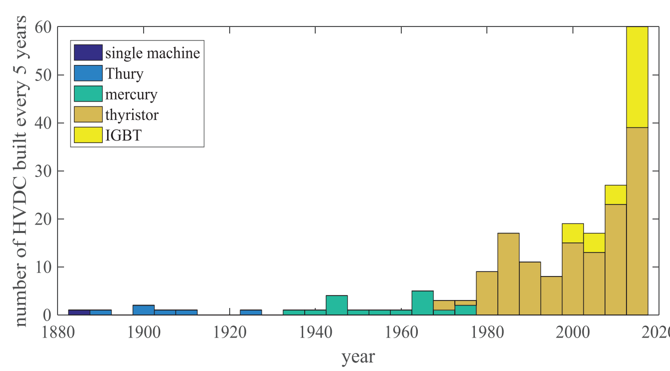

Fig. 1. Number of HVDC lines by technology built in periods of five years, from 1882 to 2017, based on information available in *[14]*

In the North American Western Interconnection, several new HVDC line projects have been proposed, as reported in the WECC Transmission Project Information Portal [99]. Additionally, there have been proposals for a conceptual HVDC national overlays, also called HVDC macrogrid [100], [101], [102], [103]. Specifically, the TransWest Express Transmission line, ±600 kV, has construction scheduled for 2018–2020 [104]. After construction of this new line, the North American Western Interconnection will have a total of four HVDC lines in operation.

In several regions of the world, HVDC systems embedded in ac interconnections are growing, reinforcing the recent historical tendencies.

VI. Conclusions

The research literature surveyed in this paper shows a progression from research to application. Early investigators were not sure of the damping benefits; nowadays it is more a matter of system design, and the benefits are perceived as certain. In the case of point-to-point HVDC lines, the damping technology has been both modeled and demonstrated for the case where a line is between areas that show oscillations. Nevertheless, for both point-to-point and MTDC configurations, several questions remain:

- How robust is the damping system? How will it operate under a variety of adverse conditions? What if there is a communication problem? How will the controls interact with system protection?
- To what extent can the power be modulated? What are the limiting factors on the ac side and the dc side? Are short-term limits different from long-term limits?
- What are the factors that limit the usefulness of modulation? How different are they from case to case?
- How would HVDC modulation for damping interarea oscillations affect other power systems problems, such as transient stability or frequency regulation?
- As more HVDC lines are installed, will it be possible to coordinate their operation?
- As MTDC configurations are built, what new applications are needed to take full advantage of their controllability?

The state of the art is still evolving, and as experience is gained in the real world, feedback may cause some revisions to what is now accepted. But the interest shown by these many researchers is cause for encouragement. Future challenges will surely be met.

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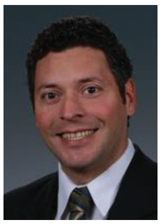

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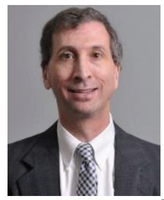

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