DEVELOPMENT OF HVDC TRANSMISSION TECHNOLOGY IN INDIA

K.R. Padiyar

Introduction

High Voltage Direct Current (HVDC) power transmission made a modest beginning in 1954 when a 100 kV, 20 MW DC link was established between Swedish mainland and the island of Gotland. The converter stations utilized mercury arc valves which were not very reliable due to the problem of arc backs. Yet, 6000 MW of HVDC links (including the Pacific Intertie in USA and Nelson River Bipole 1 in Canada) were built using mercury arc valves till 1972. The thyristor valves were first installed in a Back to Back (BTB) HVDC link at Eel River in Canada which interconnected Hydro Quebec system and the New Brunswick electric power system. Thyristor valves did not have the problem of arc backs which had prevented fast control of power in the DC links. Also, the thyristor valves are made up of series connection of thyristor devices and permitted the choice of the voltage and current ratings of the HVDC link for a specified power flow. Further developments in the technology involved microcomputer based converter control, light triggered thyristor (LTT), capacitor commutated converter (CCC) and UHV DC transmission (at ± 800 kV).

The advantages of HVDC transmission are primarily due to (a) elimination of reactive power requirement for the DC line which implies elimination of reactive power compensation (b) asynchronous connection between two AC systems (c) the fact that, for similar and voltage and current ratings, two DC conductors can carry approximately same amount power as three conductors in an AC line and (d) fast controllability of power flow which can be used to stabilize AC systems. The first advantage is useful for applications in sea crossing while the second advantage dictates its use when the nominal frequencies are different (as in different islands of Japan). The third and fourth advantages are useful in long distance bulk power transmission and HVDC ties for system interconnection. There are at present, more than 1,30,000 MW of power flow in over 140 HVDC links in the world.

In this article, I describe the introduction of the HVDC transmission technology in India and an account of my involvement with it which lasted till 1994. My interest in HVDC started when I attended the lectures by Prof. John Reeve in 1968 and subsequently read the book by Dr.Kimbark in 1971. Although my PhD work was not on HVDC, I had interaction with friends working in this area. In 1973-74, I worked at University of New Brunswick, Fredericton, as a Research Associate. My work involved the development of software for the

stability studies of AC-DC systems. The work was interesting not only because it was novel, it involved study of the Eel River link with cooperation from the local utility. The highlight was the comparison of the simulation results with field test results. I presented a paper in the Summer Power Meeting in 1974 at Los Angeles and another paper (based on analytical work) at the Conference in Montreal towards end of 1974.

Introduction of HVDC Transmission in India

The development of HVDC technology has been slow to start although there was awareness about the advantages of HVDC transmission for specific applications. For example, the possibility of a HVDC interconnection between Sri Lanka and India was discussed. However, when I returned to India in 1976 to take up a faculty position at IIT Kanpur, not much activity was going on. As a matter of fact, some electricity boards opposed the introduction of HVDC transmission as it was considered High Technology and not appropriate for India. It was felt that the introduction of HVDC technology may not happen in the 20th century!

However, I was keen to initiate research activities. I introduced a graduate course on HVDC power transmission and started guiding M.Tech and PhD students on topics related to modelling and control of converters for stability enhancement in AC-DC systems and issues related to AC-DC system interactions involving sub-synchronous frequencies. The research activities were supported by a small grant from CSIR and partially from a DST sponsored project. We could buy a small HVDC (physical) Simulator for academic use. Couple of M.Tech theses were based on the experimental work using the Simulator. Lectures were also organized in short term courses for the benefit of engineers from power industries and teachers from Engineering Colleges. There were also invitations for Lectures on HVDC transmission in Conferences and Seminars.

I came to know in early 1982 that DOE,-BARC-BHEL had teamed up to prepare a proposal to set up an Experimental HVDC Line. I also met Mr. M.S. Vasudeva in DOE and Mr. Seshadri in BARC (Reactor Control Division) who also had interest in developing power electronic controls for Indian Railways and also for power transmission equipment. In the latter half of 1982, there was a meeting of Planning Commission chaired by Dr. M.G.K. Menon to discuss the proposal and the Directors of three academic institutions - IIT Kanpur, IIT Bombay and Indian Institute of Science, Bangalore were invited. I had the privilege of attending this meeting on behalf of the Director of IIT Kanpur. In this meeting, a decision was taken to initiate the National HVDC Project with the experimental line as the major component. This project was cleared on 1st October 1984 by the Government of India with following objectives:

1) To build up knowhow for the design and construction of the various hardware components constituting the HVDC system
2) To develop better understanding of the hardware and software involved in HVDC systems, enabling scaling up to higher voltage and power levels.

3) To become conversant with the installation, commissioning and operation of HVDC systems, which will act as a basis for the same purpose for commercial HVDC lines.

In the first phase of the project, one of the two 220 kV AC circuits linking Lower Sileru in Andhra Pradesh with Barsoor in Madhya Pradesh will be converted to DC by bunching the 3 conductors into a DC pole, which will be used to transfer 100 MW at 100 kV DC with ground return covering a distance of 196 km. It was planned to further augment the capacity of the system to 200 MW at 200 kV DC monopole in phase II, The entire system including System Engineering, software and hardware was handled by a multi-disciplinary team of Indian engineers and specialists, and involved agencies like DOE, DAE. DPE, DOP, DST, NTPC, CEA, CPRI, Planning Commission, APSEB, MPEB, CSMRS, BHEL, Suppliers both in Public and Private Sectors, and Research and Academic Institutions.

Initiation of Research & Development Activities

Even before the project was approved (in 1984), activities were initiated by DOE to invite experts. One of the first expert to visit DOE was Dr. Narain Hingorani, Vice-President of Electric Power Research Institute (EPRI) at Palo Alto, California. He had obtained his PhD from University of Machester, Institute of Science and Technology (UMIST) and his thesis (which was published jointly with his guide Prof. Colin Adamson) was the first book on HVDC in the English language. He was later invited by the Bonneville Power Administration (BPA) to commission the first HVDC (long distance) link, the 'Pacific Intertie' in United States (from Celilo in Oregon to Sylmar in California, transmitting 1440 MW at ± 400 kV over a distance of 1372 km). I had the opportunity of meeting him in December 1982 at DOE office and discussing some issues. Later I had the opportunity to talk to him in detail at his house when I was a Visiting Scholar at University of California Berkeley in the summer of 1983... I also met Dr. John Vithayathil at BPA in 1983 again (I had met him earlier in the summer of 1982) and he was very helpful in answering my queries and showing me the facilities of BPA (the energy control centre and the high voltage test facilities). Both Dr. Hingorani and Dr. Vithayathil were kind enough to send me the technical literature published by EPRI and BPA respectively. I had also visited IREQ (Hydro Quebec Research Laboratory) in Montreal in 1980 and 1982. I could meet and interact with Drs. P.C.S. Krishnayya, P.S. Maruvada, V.K. Sood, H. Nakra and visited the laboratories where significant work on the HVDC line effects and modelling issues were being investigated. I also met Dr. Suresh Kapoor who was working at General .Electric on HVDC projects. In 1980, I also visited University of Waterloo and met Prof. John Reeve and his students who were working on control problems. Subsequently, in 1981, two of my M.Tech students at IIT Kanpur were selected for the PhD program in HVDC transmission at Waterloo. One of them Dr. Ram Adapa is presently in Electric Power Research Institute in charge of HVDC and FACTS program. The other could not take up the offer at Waterloo due to personal reasons, but left a year later to University of Manitoba, Winnipeg and

obtained PhD degree under the guidance of Prof. R.M. Mathur and subsequently returned to IIT Kanpur as a faculty member.

In the summer of 1982 also, I had visited San Francisco to present an important paper on the representation of converters based on graph-theoretic approach for the simulation of two and multiterminal HVDC systems. Interestingly, Mr. Woodford from Manitoba Hydro also had presented a paper on the Digital simulation of DC links based on EMTP (Electro-Magnetic Transients Program) type approach. Subsequently, the Manitoba HVDC Research Centre situated at University of Manitoba brought out a program called EMTDC which is a commercial computer program under the title 'PSCAD'.

Visiting Professor at Indian Institute of Science

After the Planning Commission meeting in 1982, I received an invitation by Professor Joseph Vithayathil (who was my teacher during my M.E. student days) at Indian Institute of Science, Bangalore, to join as a Visiting Professor for a year. I accepted the offer and joined the EE Dept. as a Visiting Professor in August 1983. I took sabbatical leave from IIT Kanpur for a year. My stint at IISc was very fruitful. I gave a set of lectures on HVDC Power Transmission. These were attended not only by the students and some faculty members (from EE and HV departments), but also by engineers at BHEL and CPRI. Dr. Arunachalam and Mr. Baldev Raj from had several discussions with me and an outcome of these discussions was a request to assist in the design of HVDC valves under a consultancy project with participation by Prof. K. Parthasarathy, Prof. Ramakrishna Iyengar and Dr. V.T. Ranganathan in the EE department. The project started towards the end my stay at IISc, but I continued to participate even after I returned to IIT Kanpur towards end of July 1984.

I also participated in two Workshops, one organized by Profs. K. Parthasarathy and H.P. Khicha, on "Electromagnetic Transients" and other by Prof. D.P. Sen Gupta on "Power System Reliability". Prof. H.W. Dommel was the visiting expert from University of British Columbia, Canada in the former Workshop and Prof. M.P. Bhavaraju from U.S.A was the visiting expert in the Workshop for the latter. Incidentally, I was teaching a course on Reliability based Power System Planning at IIT Kanpur. I was also studying the reliability issues in HVDC power transmission. I gave an invited lecture in New Delhi (organized by IEEE section) in January, 1984, describing the reliability issues in HVDC transmission systems. I recall meeting Mr. Jain, Chairman, Central Electricity Authority who appreciated the presentation and advised his Chief Engineer to interact with me.. However, that did not materialize except on formal occasions.

After Dr. M. Ramamoorty joined CPRI as Director General in January, 1984, I also had opportunity to give lectures at CPRI and interact with the engineers, particularly from the power system division.

Visit to Canada and U.S.A. in Summer of 1984

Towards the end of my stay in IISc, I had an opportunity to attend an International Conference on DC Transmission in Montreal in June 4-8, 1984. There was a large contingent from India from BHEL, CPRI, DOE, SEBs etc. who

attended. There were several papers presented in addition to a panel discussion at the end. There was a visit to the newly commissioned Chateauguay HVDC BTB (Back To Back) converter station which had a SVC (Static Var Compensator) to regulate the bus voltage as the station was connected to a weak AC system. It was a very useful visit and the Conference gave an opportunity to discuss with Engineers from utility and manufacturing industries in addition to experts from academic and research laboratories. After the Conference, I visited several places including University of British Columbia (where Prof. Dommel was my host and one of my M.Tech student , Subroto was registered for PhD under his guidance),

University of Manitoba (where Prof. R.M. Mathur was my host and Dr. Kalra was doing his PhD under his guidance). I gave lectures at both universities and met some of the young faculty members including Dr. A. Gole. The highlight of my visit to Winnipeg was the visit to the two Nelson River bipoles side by side (one with mercury arc valves and the other with thyristor valves). I could collect useful literature on the detailed converter control systems for the converter station which I passed on to Engineers at BHEL-ED. I was told later that this information was very useful in designing the controllers for the National HVDC project.

I also could get an invitation to visit GE at Schenectady in New York State because of Dr. Suresh Kapoor who was my contemporary at University of Waterloo. I visited the HVDC Simulator facility used for the design of control and protection .in converter stations. I also met my friend Dr. R.S. Thallam who provided me the literature on DC arrestors used for valve protection. I was staying with Mr. K.J. Rao who did M.Tech from IIT Kanpur and was also working at GE. He was hosting me officially!

Return to IIT Kanpur

At the end of July 1984, I returned to IIT Kanpur as my sabbatical leave got over. Although I was offered (by invitation) a Professorship at IISc, I could not accept as I had signed a bond to serve at IIT Kanpur for 3 years after returning from the sabbatical leave. During my absence, Dr. Sachchidanand (who was my PhD student) had been selected as an Assistant Professor. We applied for a major project from the Department of Electronics (as IIT Kanpur was one of the three major academic institutions selected for Research & Development under the National HVDC Project). It took some time to get the project sanctioned and start ordering for equipment. I continued to teach the elective course on HVDC Transmission which had a good response from research students. J. Senthil joined as a PhD student and started work on the elctro-magnetic transient simulation of AC-DC systems that also included study of Sub-Synchronous Resonance (SSR).

After the NHVDC project got approved in 1984, Workshops were being conducted every year on HVDC where experts from abroad were also invited. In January 1985, the first Workshop was held in Bangalore, organized by CPRI. The second Workshop was held in early 1986 at IIT Bombay and in January 1987, we organized the third Workshop at IIT Kanpur. Drs. Narain Hingorani and John Vithayathil were the experts who attended. Dr. Hingorani gave a spell

binding lecture on the State of the Art in HVDC technology which lasted about 3 hours! It was a brilliant performance and also offered insight into the power semiconductor technology research, which can revolutionize the HVDC technology in future. Dr. Vithayathil gave lectures on HVDC breakers and the issues involved in the clearing DC faults.

Transition to IISc

I received the offer from Indian Institute of Science towards end of 1985, but I could join as Professor in the Department of Electrical Engineering only on 31st July, 1987 due to my constraints. After joining, I applied for projects from two sources- Ministry of HRD and DOE. Since it takes time to process the applications, I got busy with writing the book on 'HVDC Power Transmission Systems' for Wiley Eastern Publishers (who had accepted my proposal in 1985). I could finish the manuscript by end of July, 1989 and it was published in March 1991.I was nominated a Member of the Project Review and Coordination Committee (PRCC) for the experimental line project, chaired by Dr. M. Ramamoorty, DG, CPRI. The meetings were held primarily at the Project sites (Lower Sileru in Andhra and Barsoor in Chattisgarh).The experimental HVDC line between Lower Sileru and Barsoor transmitted power first time on 3rd October, 1989. This was the first HVDC line India.

I also started teaching the elective course on HVDC Transmission and guiding M.E. projects and research students. Three of my PhD students who had registered in IIT Kanpur started visiting me for consultations. Two of them, Dr. Rajiv Varma (presently at University of Western Ontario in Canada) and Dr. J. Senthil (presently at Power Technologies, Schenectady, U.S.A.) also conducted experimental work on the ABB HVDC Simulator in CPRI .The results based on the physical simulator were used to authenticate the system models and the analysis. The work carried out was published in journals.

The research activity picked up after the projects got approved in 1989. The DOE project was aimed at the study of Multi-Terminal DC (MTDC) systems which were under consideration in N. America. The research work related to developing a systematic approach to the study of power flow, stability (including synchronous and voltage stability) of AC systems interconnected by MTDC systems. In particular, the work required development of suitable software. Specifically, an electro-magnetic transients program called DISIPACK was developed to study the transients in two and multi-terminal DC systems. Utilizing the concepts of Object Oriented Programming and graph-theoretic representation of converters, the computer time was reduced significantly and the program could run on PC-AT with 20 MHz clock. This work was presented in 1990 NPSC (National Power Systems Conference) held in Mumbai. A simpler version of the program was applied for the understanding of the response of HVDC converters for various disturbances. A short term course was conducted in 1992 which was attended by faculty from engineering colleges and engineers from industry including State Electricity Boards. In 1991, after my HVDC book was published, I got an invitation from Prof. M.A. Pai at University of Illinois, Urbana, to give a set of lectures spread over 3 weeks, based on the book. The lectures were attended by research students

and the faculty in the power area. I also visited Massachusetts Institute of Technology at the invitation of Professors George Verghese and Marija Ilic and I gave two lectures. I visited EPRI in Palo Alto at the invitation of Dr.Hingorani and interacted with the research groups working on HVDC and FACTS. In September 1991, I attended the IEE Conference on 'AC and DC Transmission' to present two papers and visited the Sellindge terminal of the Cross Channel Scheme transmitting 2000 MW power (from France to U.K.). I also visited Liege University in Belgium at the invitation of Prof. Mania Pavella and delivered a lecture (and interacted with the power group there).

By 1996, two of my PhD students working on Voltage Stability and Harmonic Interactions in HVDC –AC systems, completed their work and published their work in conferences and journals.

Epilogue

I consider the National HVDC Project as a mission oriented project was a successful experiment and introduced the HVDC technology for power transmission in India. The attitude of system planners in Indian Electricity Boards changed drastically and the first commercial scheme of a BTB HVDC link at Vindhyachal interconnecting Northern and Western Regions was commissioned in 1988. Subsequently, 6 more BTB links among regions and 4 Bipoles were built and are operating. A UHV (+/- 800 kV) DC , three terminal scheme is being built to transfer 6000 MW of hydro power from North east to load centre around Delhi. There is also a private HVDC bipole transmitting 2000 MW power from Gujarat coast to Haryana. HVDC interconnections are also being built between India and Bangladesh, India and Sri Lanka.There are also 6 TCSCs and the all the 5 regions are now synchronized into one National Grid.

In 1994, I introduced an elective on FACTS Controllers. Dr. Hngorani had given the concept of FACTS (Flexible AC Transmission Systems) in 1988 which involved the application of power electronic controllers to enhance power transfer, improve voltage regulation and system security of AC transmission systems. The first generation FACTS Controllers are SVC (Static Var Compensator) and TCSC (Thyristor Controlled Series Capacitor) based on thyristor valves. The second generation of FACTS Controllers are based on the application of VSC (Voltage Source Converter) using IGBT valves. A STATCOM (Static Compensator) is an advanced version of SVC which has better technical performance with smaller foot print. FACTS Controllers can also be applied in distribution systems to improve Power Quality (PQ). Such devices were labeled as Custom Power Devices by Dr. Hingorani in 1995. Interestingly, just as HVDC technology resulted in the development of SVC and TCSC, the STATCOM technology led to the development of VSC-HVDC which has several advantages over the LCC (Line Commutated (Current Source) Converter) based HVDC technology. VSC-HVDC (which was first applied in 1997 with a modest rating of 3 MW) is now being applied for transfer of power from off-shore wind power plants. Since 2010, with the development of Modular Multilevel Converters, the ratings have gone up to 1000 MW. There is convergence between FACTS and HVDC in that two STATCOMs connected in parallel can also be used as a BTB connected VSC-HVDC scheme. Incidentally, at the persistent request from

my publisher in Delhi, I revised my HVDC book extensively, incorporating the later developments in the second edition published in 2010. A subsequent revision published in 2014 includes the topic of MMC based VSC-HVDC.

There were several Masters and PhD students who worked on FACTS for system stability improvement, based on designing appropriate locations and control strategies for voltage regulation, prevention of blackouts, damping SSR and improving power quality. Couple of students also worked on VSC-HVDC. I had three DST projects to support the activity and in 2007, published a book on "FACTS Controllers in Power Transmission and Distribution". While it was a pleasure to teach and guide students in new technologies and their applications, it was also very satisfying to be associated with the development of the HVDC technology through NHVDC Project in India. Two of my PhD students, Prof. Rajiv Varma and Anil Kulkarni were consultants in the SVC and TCSC projects developed by BHEL in the nineties.