HVDC Simulation and Control System Testing Using a Real–Time Digital Simulator (RTDS)

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Abstract – **This paper reports on a recently completed evaluation study in which physical High Voltage Direct Current (HVDC) controls were interconnected to the Real–Time Digital Simulator (RTDS™). The study was performed jointly by RTDS Technologies Inc. of Winnipeg, Canada and ABB Power Systems AB of Ludvika, Sweden. In the past such a study could only have been performed using an analogue HVDC simulator. The recent introduction of an accurate and flexible real–time digital simulator has however made it possible to perform this study, and many others like it, in a new, more efficient manner.**

I. INTRODUCTION

High Voltage Direct Current (HVDC) transmission was introduced more than forty years ago with the installation of the Gotland Scheme in 1954. When integrated with conventional ac transmission technology HVDC offers many advantages and benefits to the overall power system. Many of the benefits which are realized can be attributed to the fast, flexible and effective means by which HVDC systems can be controlled. It is therefore accurate to say that one of the most important considerations when designing an HVDC installation is the application of appropriate controls and protection strategies. Although the overall control concepts are well developed and well understood, each new installation brings with it new challenges which must be met, for the most part by the application of specialized control features.

Recognizing the importance of correct and reliable control system operation in HVDC transmission systems, much effort is made to extensively test proposed control principles as well as the actual control hardware before installation in the converter terminal stations. Historically, tests have been performed using both on–line analogue HVDC simulators and off–line software based digital simulation programs. The recent introduction of real–time digital simulation techniques has provided a new study method which combines the real–time operating features of analogue HVDC simulators with the accuracy and flexibility of digital simulation programs.

II. SIMULATION TECHNIQUES

The need to test measurement protection and control devices before final installation in the real power system has long been recognized by both utilities and equipment manufacturers. Many different facilities and approaches exist and are commonly utilized to accomplish such pre–installation testing. Depending upon the particular device being considered and the particular application of the devices, different test methods and facilities might be required.

Analogue HVDC simulators and ac Transient Network Analyzers (TNA) have been widely used throughout the power system industry over the past several decades. Although there are certain inherent difficulties and limitations associated with the application and utilization of analogue simulators, many industry tests which require real–time response are performed using these techniques.

In their simplest form, analogue simulators are scaled down physical models of the actual power system. Individual simulator components are connected together to mimic interconnection of real devices within the power system being studied. Typical simulator installations might include models of voltage sources, synchronous machines, transformers, transmission lines, circuit breakers, passive filters as well as many others. In the case of HVDC simulators, models of converter valve groups including converter transformers, thyristor valves, valve arresters and snubber circuits are also required. Determining the size or extent of the model required to adequately represent the system under study requires application of engineering experience and judgement. Network reduction and equivalencing techniques then must be applied before the overall simulator model can be defined.

Voltage, current and power levels of analogue simulator installations vary widely. Lower ratings are advantageous from both the point of view of cost and safety but increase the difficulties associated with system losses. Because component scaling results in disproportionately high losses, a means for compensating or reducing component resistance must be implemented. Loss compensation methods, when properly designed and applied do achieve the goal of reducing resistance values to acceptable levels but at the same time increase the difficulties associated with model set–up, adjustment and verification.

In addition to the results obtained from analogue simulator studies, manufacturers, utilities and researchers rely heavily on digital computer simulations to study the performance and operation of proposed and existing electrical power systems. A wide range of digital simulation packages are available to study nearly all aspects of power system planning, design, development and testing. Of particular interest in the context of this paper are digital simulation programs associated with electromagnetic transient phenomenon such as EMTP [1] or EMTDC [2]. The concepts and underlying algorithms which form the basis of virtually all electromagnetic transient simulation packages are based on a technique introduced by H. Dommel in his well known paper of 1969 entitled "Digital Computer Solution of Single and Multiphase Networks" [3]. In these solution techniques inductors and capacitors are modelled as current sources (I_H) in parallel with resistors (R) as shown in Fig. 1. Similar representations exist for other devices such as transformers, transmission lines, etc.

When the overall network is broken down into resistors and parallel current sources, nodal equations can conveniently be derived and a nodal admittance matrix solution can be performed. The simulation progresses in a sequential manner, where the voltage across an element results in a current injection (I_H) for each element attached to a particular node. The current injection terms for each node are summed together to form an entry to the so–called current injection vector. The entire current injection vector is subsequently multiplied by the inverted conductance matrix to form a new voltage vector as illustrated in Fig. 2. The newly computed entries in the voltage vector represent the system conditions at the beginning of a new simulation timestep Δt. In this manner a new solution for the power system is produced at discrete instants in time, with the duration between consecutive solutions being defined by the chosen timestep Δt.

Until recently, digital electromagnetic transient simulations were limited to non–real–time operation hence severely limiting their application in the area of physical equipment testing. Non–real–time operation implies that an event which normally takes only msec in the actual power system might take much longer (many seconds or minutes) to simulate using the EMTP or EMTDC program. Since meaningful testing of physical control or protection equipment almost always requires the simulated waveforms to be input to the device in real–time, digital electromagnetic transient programs have been of little use in these areas.

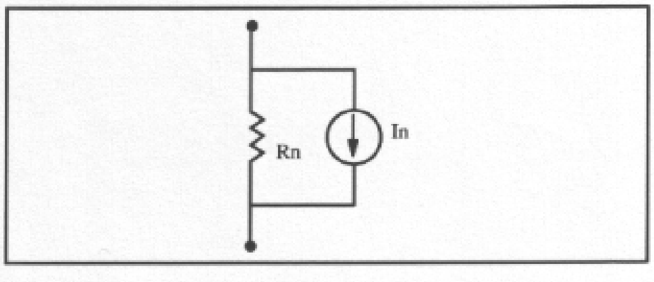

Fig. 1. Norton Equivalent Representation

$$\begin{bmatrix} \mathbf{V} \end{bmatrix} = \begin{bmatrix} \mathbf{G} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{I} \end{bmatrix}$$

Fig. 2. Nodal Admittance Solution

Recent advances in digital signal processing technology as well as advances in the application of parallel processing techniques have had a profound effect on the achievable speeds with which computations can be performed. Much effort has been made in both hardware and software solution techniques as applied to the study of electromagnetic transients, with the end goal being a simulation tool which can achieve sustained real–time operation. Several approaches have been proposed and studied [4] [5] [6] with varying degrees of success. One of the key difficulties which must be overcome in any design relates to the appropriate choice of a simulation timestep (Δt). Smaller timesteps increase both the accuracy with which the system is represented and determine the maximum representable frequency response. On the other hand, since all mathematical computations involved in the system solution must be performed once per timestep this implies that as the timestep is reduced the computational speed of the simulation device must increase. Furthermore, as the represented power system grows, its overall conductance matrix grows and hence the number of computations which must be performed in each timestep increases.

The Real–Time Digital Simulator (RTDS) used in the study being described in this paper is based on a parallel processing hardware architecture and utilizes many high speed Digital Signal Processors (DSPs)[7]. The concept of mathematically isolated sub–systems is used to help distribute the computational burden amongst processors and groups of tightly coupled processors which reside on racks of hardware. Sub–systems are typically linked to one another using transmission line models or other suitable components such as HVDC converters. One of the most significant advantages of this parallel design and solution approach is that larger and larger power systems can be represented without significantly effecting the simulation timestep Δt. The RTDS simulator typically operates with timesteps ranging between 45 and 75 μsec. All simulations performed during the study being presented here were run using a 68 μsec timestep.

III. SIMULATION SET UP AND TEST FACILITIES

All tests described and presented in this paper were performed using the real–time digital simulator developed at the Manitoba HVDC Research Centre (Winnipeg, Canada) [8]. Physical HVDC Converter Firing Controls (CFC) for one bipolar HVDC system were provided by ABB Power Systems AB (Ludvika, Sweden). Most of the tests performed required simultaneous operation of the RTDS and the CFC in a fully interconnected manner hence requiring a large number of analogue and digital signals to be continuously exchanged between the two devices.

In any HVDC equipment supply contract, the manufacturer supplying the conversion and control equipment must perform many simulation and factory system tests prior to installation and commissioning of the equipment at the site. As part of these pre–commissioning tests, a dynamic performance study of the proposed HVDC controls must be performed. Such a study requires real–time simulation capability since a set of real HVDC controls identical in functionality to those being proposed must be extensively tested. During the tests, the performance of the controls is monitored, recorded and evaluated. Based on observed results, parameter adjustments are made so as to satisfy specific criteria put forth for the particular project.

The work presented here is typical of that which would normally be performed during a dynamic performance study. Model verification and validation, control system interconnection, steady state operation and performance of controls under various disturbances were all considered during the course of the study.

Fig. 3 shows, in the form of a basic single line diagram, an overview of the power system model used during testing. Two closely coupled HVDC transmission systems along with substantial ac system representation were included. Within the ac system model several synchronous machines (complete with exciters, stabilizers, governors and turbines), transformers, transmission lines, circuit breakers, filter banks and voltage sources were included. One of the HVDC systems was controlled using ABB's external converter firing control equipment while a second was controlled internally using a set of generic HVDC controls included in the standard RTDS component library.

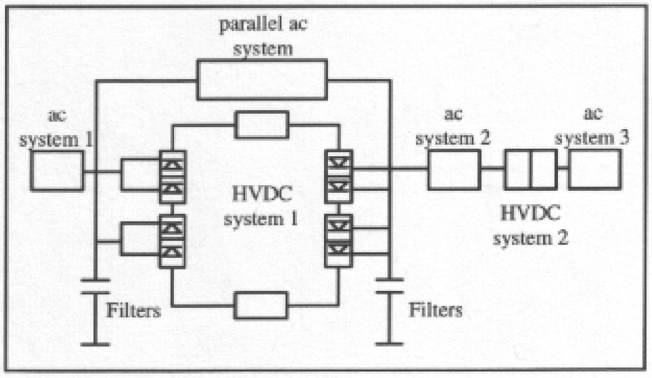

Fig. 3. Bipolar System Model

In order to adequately represent the system configuration outlined in Fig. 3 several racks of RTDS hardware were required. Every so–called rack contains eighteen tandem processor cards, each of which in turn house two DSPs. As the size of the system being represented grows, the number of DSPs required to solve the mathematical equations increases. Since the number of required racks is dependent on the size and configuration of the power system being modelled, RTDS installations can consist of as little as one rack. If very large system models are required then many interconnected racks must be used. During the current tests as many as five racks were used simultaneously.

Since ABB's physical CFC equipment was used to control one of the HVDC systems, a significant number of analogue and digital signals were passed between the CFC and the RTDS. In its simplest form, the connection between the RTDS and the CFC for a bipolar HVDC system would require exchange of valve firing pulses (48 digital signals input to RTDS), measured ac commutating bus voltages (12 analogue signals output from RTDS), measured dc currents (4 analogue signals output from RTDS) and measured dc voltages (4 analogue signal output from RTDS). In a practical application such as the one being reported in this paper, many more analogue and digital inputs and outputs might be required, examples of which might include:

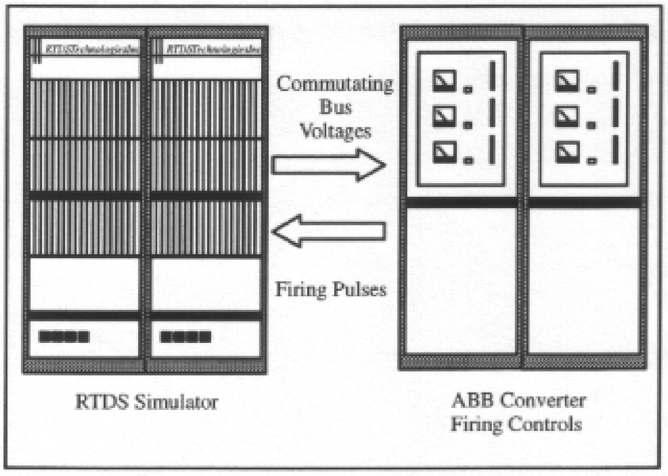

Fig. 4. RTDS/CFC Hardware Connection

i) converter transformer tap position indication signals (output)

ii) current zero crossing pulses for gamma measurement (output)

iii) event timing signals from controls for capture on RTDS data acquisition system (input)

iv) event trigger signals for initiating certain control system actions (output)

v) angle measurements as produced by controls for capture on RTDS data acquisition system (input)

vi) measured valve winding currents or their computed derivatives (output)

Interfacing of many other specialized or specific signals may be required, depending on both the control philosophies used and upon the types of tests being performed. Fig. 4 illustrates the basic RTDS/CFC interface used during testing and includes some of the signals which were interfaced.

It is evident from the preceding paragraph and from Fig. 4 that in order to effectively and efficiently perform HVDC control system tests, the simulator facility must lend itself well to connection of analogue and digital I/O signals. Having recognized this requirement at the design stage, the RTDS includes sufficient and easily acceptable I/O. Each tandem processor card is equipped with eight scaleable analogue output ports, two 16–bit digital input ports, and two analogue input ports. Because the analogue input channels are less frequently used, they are installed as optional items depending on the customers specific requirements. The total number of I/O points on each rack of RTDS hardware is therefore;

– analogue output channels → 144
– 16–bit digital output ports → 36
– 16–bit digital input ports → 36
– analogue input channels → 36 (maximum)

IV. STUDY TEST CASES AND RESULTS

The joint study performed by RTDS Technologies Inc. and ABB Power Systems AB involved several phases. Each phase in itself represents a fairly comprehensive study and plays an important role in the accuracy and validity of results obtained from the final full system tests.

A. Transmission Line Data and Model Validation

The first set of tests performed were aimed at validating transmission line models and verifying that data for each model was correctly entered. Line data was provided in one of two different formats depending on information which was available at the start of the study.

Some of the transmission line data was provided as equivalents in the form of positive sequence passive component values (ie: R, L, C). Since the most accurate and flexible methods of line modelling on the RTDS involves travelling wave representation, the data was transformed accordingly. All such lines were assumed to be ideally balanced and a typical relationship between positive sequence (metallic mode) and zero sequence (ground mode) component values was applied to define the zero sequence data.

The second set of transmission line data was provided in the form of geometrical configuration and conductor layout. This form of data is well suited for use on the RTDS since a graphically driven transmission line constants program (T–Lines) exists as part of the PSCAD interface package. Conductor data is entered into the T–Lines program and then compiled to produce an output format which fully defines the line for use with travelling wave algorithms. Frequency dependent line models [9] can be defined and used where required although they require twice the processing hardware required by standard Bergeron travelling wave models [3]. For the study at hand, all travelling wave ac lines and line sections were represented using Bergeron models while dc line sections were represented using frequency dependent line models.

Several tests were performed on each line model in order to verify its impedance at fundamental frequency as well as some other low order harmonics. In addition, the frequency characteristics of line configurations were checked using the RTDS off–line companion program EMTDC.

B. Synchronous Machine Model Validation

The second set of tests performed were aimed at validating synchronous machine models and their associated control modules (ie: exciters, power system stabilizers, governors and turbines). In addition to validating the individual models, these tests also provided a method of verifying that all parameter data was entered correctly before incorporating the machines into the final system model.

Several different machines with different voltage, current and power ratings and with different excitation control systems were required. Each machine was tested and the results were compared with those obtained from an independently run off–line program. This validation procedure is the same as that normally used prior to initiation of analogue simulator studies which involve representation of synchronous machines within the simulated system.

The main machine model validation cases are included in the following tests:

– open circuit test
– short circuit test

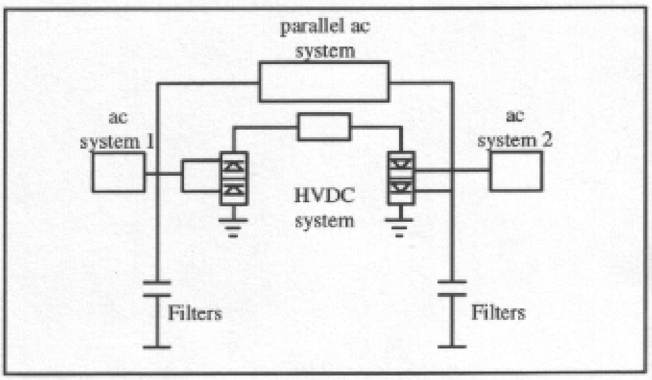

Fig. 5. Monopolar System Model

- load test
- step response test
- load acceptance test
- load rejection test

In addition to the tests described above, open loop tests were also performed on the exciter, stabilizer, governor and turbine control systems. Results from these tests were also compared with results from EMTDC cases in which individual control blocks were interconnected to represent each exciter, stabilizer, governor and turbine. These tests were intended to verify correct implementation of control system configurations as well as correct parameter or data entry.

C. Monopolar System Validation Tests

As a final step prior to the set–up and testing of the system shown in Fig. 3, a smaller and simpler system was investigated. Fig. 5 shows a basic single line diagram of the model used during the so–called Monopolar validation testing. The system includes one monopolar HVDC link controlled by one set of ABB converter firing control equipment, two synchronous machine models at the rectifier station, step–up transformers, voltages sources and ac and dc transmission lines.

The reasons for performing the monopolar validation test prior to beginning investigations involving the full system model were two–fold. Firstly, the RTDS HVDC converter model and its input data could be tested prior to including them in the larger and more complicated model of Fig. 3. Secondly, interconnection and basic functionality of the external converter firing control could be checked prior to their inclusion in the final system model. Because the firing controls consist of specialized hardware components and software models, and because the interconnection of the CFC to the RTDS involves a large number of analogue and digital signals, it is necessary to ensure that no problems exist in each portion of the overall test set–up prior to initiating final tests. The monopolar validation study was seen as a convenient method of ensuring correct operation and interconnection of equipment to be used in the final study.

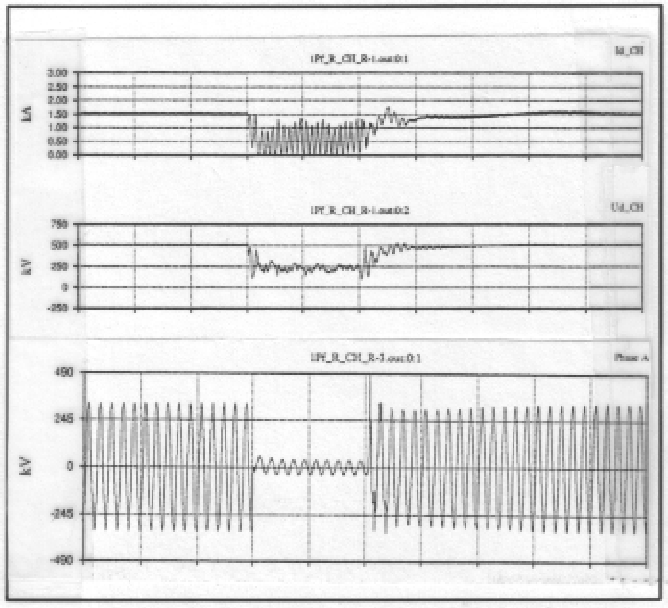

Fig. 6. Typical Output from Monopolar Study

Results obtained from the monopolar validation tests were again compared with results from independently run simulation cases using both off–line digital simulations and ABB's analogue HVDC simulator in Sweden. Fig. 6 shows a typical set of waveforms captured during monopolar validation studies. The traces represent system conditions following the application of a single line to ground fault at the ac bus on the rectifier end of the HVDC link.

D. Bipolar System Validation Tests

Bipolar system test were carried out over a period of several weeks and included both steady state operation and transient conditions. Faults on both the ac and dc systems were investigated along with complicated sequences initiated by both the RTDS and the interconnected ABB converter firing controls.

Results from simulation cases were captured through the RTDS operators console and performance of the system was evaluated. Adjustments to both the physical control equipment and the parameters associated with RTDS based controls are made based on evaluation of captured results.

In the particular system model used for the validation study, both methods of control were used simultaneously (i.e. one HVDC system was externally controlled while the other was controlled by internal HVDC controls). Interaction between control action of the two HVDC systems was of particular interest during simulations.

Fig. 7 shows a set of captured waveforms from the externally controlled HVDC system. The results are typical of what might be expected when a three line–to–ground fault occurs at the inverter end ac system.

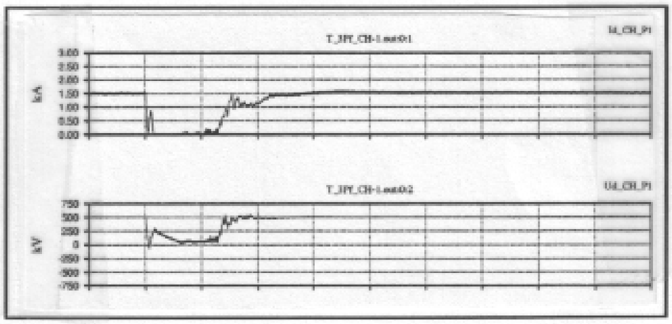

Fig. 7. Typical Output from Bipolar Study

V. CONCLUSIONS

This paper has presented some aspects of a recently concluded study in which the RTDS simulator was used to investigate HVDC system operation. A rather complex system was involved in the final set of tests and hence several steps were taken to validate difference portions of the model.

The RTDS is well suited for the study of interconnected ac/dc systems since it included accurate models for components required in both types of systems.

Conveniently placed analogue and digital I/O enables complex interconnections between physical control equipment and the simulated model.

Flexible and friendly graphical interface software facilitates operation of the RTDS. Circuit assembly and definition, system control and operation, as well as data capture and storage are all performed through the common interface platform.

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R. Wierckx graduated from the University of Manitoba with a B.Sc. in 1983 and a M.Sc. in 1985. He was employed by the Manitoba HVDC Research Centre for nine years as a Simulation Engineer and was extensively involved in the development of the real–time digital simulator (RTDS). Since the beginning of 1994 he has been working at RTDS Technologies Inc., Winnipeg, Canada, where he is a Director and co–founder of the company.

H. Duchén received his M.Sc. from the University of Technology in Dresden, Germany in 1983. Since graduating, he has been working for ABB, starting with two years of designing control and protection equipment. After this, he began working on simulator studies and the commissioning of HVDC transmission equipment for Gotland III, Fennoskan, Rihand–Delhi, Baltic and Koatishan projects. In 1994 he became involved in studies and work involving RTDS applications.

M. Lagerkvist received his M.Sc. in Electrical Engineering from Chalmers University of Technology in Sweden in 1981. After graduating he began working for ABB designing control systems and became manager of the control systems design department in 1989. In 1989 he worked as commissioning manager of the Quebec site for the Quebec/New England multi–terminal HVDC project. Since 1991 he has been manager of the system simulation department.