Synchrophasor based Power System Monitoring and Control using Real Time Digital Simulation Facility

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Abstract—**This paper briefly presents the details of Real Time Digital Simulation (RTDS) setup at IIT Kanpur to carry out research works related to wide-area monitoring and control of power system. The RTDS have been integrated with synchrophasor equipments, such as Phasor Measurement Units (PMU) and Phasor Data Concentrator (PDC) to setup Wide-Area Monitoring and Control System (WAMCS) lab. The application of this physical real time simulation facility has been demonstrated for wide area voltage stability monitoring and stabilizing control of the power system.**

Keywords-Real time digital simulation; synchrophasor; phasor measurmeent unit; wide-area monitoring and control;

I. INTRODUCTION

THE evolution of power system from an isolated and simple radial architecture to large interconnected system has significantly reduced the downtime and facilitated efficient transfer of power from the remote generating stations to the load centers. However, it has made power system operation and control more complex. Study of the dynamic and steady state behavior of such a large network, sometimes, becomes impractical if the system study is carried out on its simple and reduced equivalent model, specifically while analyzing the stability of the system and designing of controllers. Various controllers and stabilizers operate at much lower voltage and current level than that in the actual power system. The actuating signals of these controllers and stabilizers are often amplified to match the control voltage in the power system. Hence, tuning of these devices could be carried out easily if a low voltage emulation framework is available that could mimic the behavior of the actual system under study. Such a scenario of rapid hardware prototyping led to the development of real time simulator for the power system applications.

The real time simulator model of the practical power system utilizes a set of Differential and Algebraic Equations (DAEs), through which the selected input can be interfaced to a real world voltage stimulus and output of interest can also be extracted for the real time monitoring purpose. The DAEs are solved numerically at discrete time steps and the new values of the input and the output signals are updated for each time step. The physical system, which is required to be validated, interacts with the emulator through the input output signal channels with proper conditioning. For the stimulus and response pair to work properly in the closed loop, it is required that the emulator solves the DAEs within the solution time step and report the result exactly at the ticks of the time step. This type of real time system is called hard real time system, where there is a strict constraint on the result to be reported at the timing in sync with the real world clock. The number crunching capabilities of the emulator should be sufficient enough to solve the required number of DAEs within the solution time step.

With the increase of the complexity of the system, the order of the DAEs also increases. This sometimes requires the DAEs to be decoupled and solved simultaneously in parallel processing architecture and report the results within the constraint time interval. The decrease in solution time step increases the accuracy of the system to be emulated, but due to hardware capability of the emulator, it will hit a limit where further decrease of the solution time step will not be possible. The only option available, then, is to increase the computation capability (increase in parallelism) of the emulator.

One such system emulator for power system and power electronics applications is Real Time Digital Simulator (RTDS) [1]. A six rack RTDS facility, supported by DST New Delhi, has been made operational in the Department of Electrical Engineering at IIT Kanpur. With the advent of synchrophasor technology, the real time monitoring and control of power system has become possible. The major components of synchrophasor based WAMCS include PMUs, which provide voltage and current phasor information at a speed of 50/60 frames per second [2] and the PDC situated at a control station. These equipments have also been made operational utilizing the funds from Central Power Research Institute (CPRI), Bangalore. Various research works with respect to synchrophasor based Wide Area Monitoring and Control (WAMC) of power system as well as renewable integration are being carried out using the RTDS facility.

This paper describes the features of the RTDS facility and synchrophasor based WAMC system lab at IIT Kanpur and presents the results of two specific applications on RTDS platform, viz., real time monitoring of voltage stability and wide area control of the power system.

The authors wish to thank the Department of Science and Technology, New Delhi, and Central Power Research Institute (CPRI), Bangalore, India for providing financial support to carry out this research work under project nos. DST/EE/20100258 and CPRI/EE/20100037.

II. REQUIREMNTS FOR SYNCHROPHASOR BASED REAL TIME SIMULATION

Fig. 1 shows the basic building blocks to carry out the simulation for wide area monitoring and control of power systems.

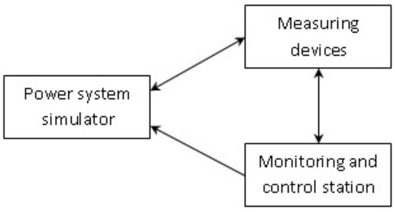

Fig. 1: Basic building blocks for real time simulation

A. *Power System Simulator*

This is an important component among others to carry out various studies on power system. Utilities/institutions have been using wide variety of analog and digital simulation tools during various stages of power system operation and control. Earlier, analog simulators were popularly used in which various power system elements were physically modeled. Analog simulators facilitated easy check on the complete system. Interaction between control equipment and system were studied on the analog simulators. However, component tolerances prevented exact representation of the original system. Adding low R/X ratio components were difficult and number of physical components required was increasing drastically with the size of the system. To overcome these difficulties, the next generation of simulators were developed using digital technology. First of its kind was open loop digital simulation. In this type of simulators, exact representation of the system, with any R/X ratio, was possible without use of physical components. Nonlinearities could be simulated exactly and size of the system for the simulation was practically unlimited. In open loop digital simulators, changes in the test conditions and signal measurements were implemented using offline calculations. This made real-time interaction between controller and modeled systems difficult or sometimes impossible [3]. With the advances in the computing hardware and sophisticated power system component modeling techniques, closed loop digital simulators were developed. In these types of simulators, with the usage of advanced digital signal processors, any size of simulation can be carried out, which will mimic the real-time system behavior. These simulators provide interaction between controllers and the modeled system.

Digital simulators run a real time operating system with user application to be distributed in multiple processors and also have a fair number of analog and digital input/output channels. The digital simulators have the flexibility to alter the system parameters easily and analyze various power system scenario of a large network. The Graphical User Interface (GUI) of the digital simulators provides an easy to use platform to pictorially describe a large and complex system on a terminal screen. The GUI also enables the user to capture the signals and provide some intuitive plots for post analysis purpose. The application code which runs in the digital simulator is developed by using interfacing software, which interacts with the digital simulator.

B. *Measurement Devices*

The purpose of these devices is to measure various electrical quantities at different locations of the power system and communicate the same to the monitoring and control station using existing communication channels. Present day Supervisory Control and Data Acquisition (SCADA) systems are using Remote Terminal Units (RTUs) to measure various electrical quantities of the system. Energy Management System (EMS) monitoring software utilizes state estimation to get the present state (voltage magnitude and phase angles) of the power system. This process takes few minutes. Hence, with the present EMS software, one gets the system state with delay and, further, the measured data do not carry any global time stamping. With the development of GPS time synchronized PMUs, the system states can be estimated in real time.

C. *Monitoring and Control Stations*

The purpose of this station is to collect the information from all the nodes of the power system and perform some monitoring and control actions. Many of the present day SCADA systems employ commercial proprietary software upon which SCADA system is developed. The proprietary software often is configured for a specific hardware platform and may not interface with the software or hardware supplied by different vendors [4]. With the implementation of the GPS synchronized synchrophasor measurements using PMUs, the structure of the software and hardware has changed and active research is under way to effectively implement WAMCS architectures along with the existing SCADA systems. A monitoring and control station can perform various operations, such as running online load flow, load forecasting, assessing the system stability, implementing demand response, preventive and/or emergency control actions based on the present state of the power system, load shedding etc. Also the monitoring and control station software and hardware must be able to translate and interpret the data, based on specific protocol drivers.

III. EXITSING FACILITY AT IIT KANPUR

A. *Real Time Power System Simulator [1],[5]*

Real Time Digital Simulator (RTDS) developed by RTDS Technologies Inc., Canada was procured to carry out research work in the area of electrical power systems, power electronics and control systems. It is a combination of specialized computer hardware and software designed especially for power system electromagnetic transients. Salient features of the RTDS are described below.

RTDS hardware: The RTDS consists of individual racks of tightly coupled digital signal processors connected to each other using a common backplane. Each rack is identical and contains the following types of cards.

- Processor card.
- Workstation interface card.
- IRC switch

The RTDS at IIT Kanpur (Fig. 2) contains PB5 processor cards and each rack contains three such cards. Each PB5 card contains two number of freescale MC7448 RISC processors and can operate at a clock speed of 1.7GHz. These cards contain 12 loading units, which allow more number of components to be included on one card. Each card can handle 72 single phase nodes or 24 three phase nodes and if each card is properly configured, it is able to simulate two networks (each of 72 nodes) simultaneously. PB5 cards are provided with 2 I/O ports and 6 communication ports, which will facilitate the user to communicate more number of other PB5 cards.

The simulator has been provided with Giga Transceiver Workstation Interface (GTWIF) card to perform communication between the RTDS and the host computer. Main functions of GTWIF include loading the case, starting and stopping the case, time stamp generation, rack hardware diagnostics, inter-rack synchronization along with IRC card. It works on 10/100 Base Tx Ethernet communications and facilitate USB access from the front panel for system diagnostics and configuration.

IRC switch stands for inter-rack communication switch and its main function is to facilitate the user to communicate among the various racks, while simulating large scale power systems. This RTDS IRC switch is capable of communicating to as many as 60 racks simultaneously.

Apart from the above compulsory cards, RTDS has been provided with the following cards to facilitate the user to interface various types of external hardware and/or software.

- GT I/O cards – used to export and import various electrical quantities and status of equipment in analog and digital forms. RTDS has been provided with GTDI card for digital input, GTDO card for digital output, GTAI card for analog input and GTAO card for analog output.
- GTNET cards – used to provide the real time communication link to and from the simulator to other hardware/software via Ethernet. The firmware versions supported by GTNET cards provided in RTDS are (a) GTNET – PMU to support C37.118 standard of PMU data, (b) GTNET – GSE to communicate with IEC 61850 compliant IEDs with GSSE or GOOSE formatted, (c) GTNET – SV to support IEC 61850-9-2 sampled value messaging for power system voltages and currents, (d) GTNET – Playback to read large data files stored on a PC had disk and allow them to be played back in RTDS, and (e) GTNET – DNP to support DNP 3.0, a SCADA protocol commonly used in substation.
- GTSYNC – used to synchronize the RTDS simulation time-step to GPS clock or some external reference.

RTDS software: RTDS software contains two components –

- RTDS operating system and compiler which runs on RTDS racks
- RSCAD – A GUI based simulator to design and run the simulations

RTDS operating system (OS) runs in a distributed manner. One part of the OS runs on host computer of RTDS rack and other part runs on the GTWIF card. RTDS compiler converts simulations to the machine executable format. Compiler also takes care of parallel processing among digital signal processors, memory allocation and communication.

RSCAD is a GUI based software tool to provide full graphical interface to RTDS. Draft module of RSCAD is used mainly for circuit assembly and parameter entry. The library section of draft module contains various pre-built power system and control components, which can be used to develop a simulation circuit in draft module. Runtime module of the RSCAD is used to control the simulation during run time, which runs on the RTDS racks. During runtime, various control operations such as fault application, breaker operation, and set point adjustment can be done using runtime module.

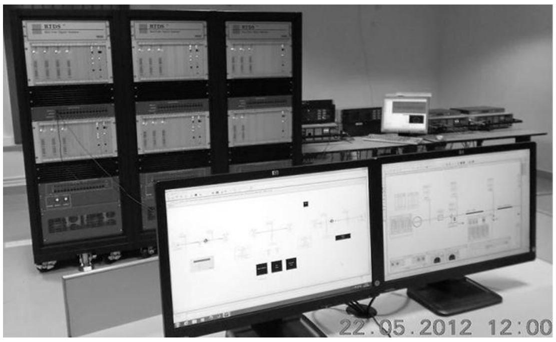

Fig. 2: RTDS lab setup

B. *Measurement Devices*

The RTDS facility at IIT Kanpur has been supplemented by the measurement devices such as PMU to interface with RTDS and other hardware for analog and digital data I/O. PMUs are synchronized with 1 PPS signal using GPS clock. The PMUs are IEEE C37.118-2005 [2] compliant. These PMUs have the capability to provide phasor data at the rate of 60 frames per second for 60 Hz system and 50 frames per second for the 50 Hz system. Some PMUs, such as SEL-421 and SEL-451 of the Schweitzer Engineering Laboratories (SEL) [6], also have the inbuilt capability of distance and overcurrent relay protection. To provide input to the relays and PMUs, RTDS analog output is amplified using amplifiers to mimic the real time conditions.

C. *Monitoring and Control Station*

Phasor Data Concentrator (PDC) receives data from various PMUs and consolidates their phasor data for wide area monitoring and control. Hardware PDC (SEL-3378 from SEL) is capable of communicating with as many as 15 devices serially and some more can be interfaced using Ethernet port. In addition to hardware PDC available in the laboratory, software PDCs such as openPDC [7] are also used to consolidate phasor data. Ideally openPDC can communicate with any number of PMUs. Also a freeware namely PMUConnectionTester [7] is useful to verify connectivity of a PMU to a particular device and acquiring data from PMU. Two more proprietary software of SEL, SynchroWave Console and Archiver, are used to monitor and store various phasor quantities. Present lab setup (Fig. 3) facilitates and uses any of the two types of the configurations shown in Figs. 4-5 to study the wide-area monitoring and control functions using the real time simulator.

Fig. 3: PMU and PDC setup

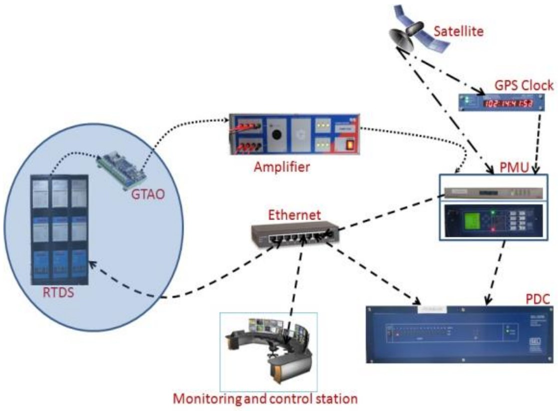

Fig. 4: RTDS lab setup for wide area system monitoring using hardware PMU

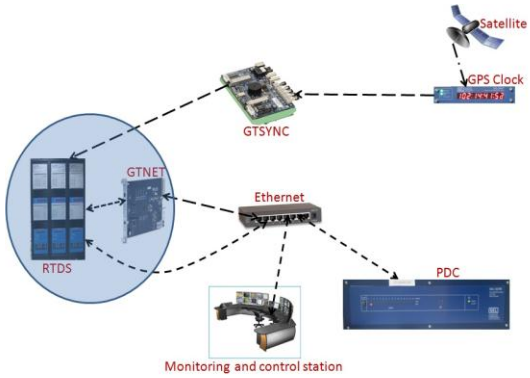

Fig. 5: RTDS lab setup for wide area system monitoring using software PMU

IV. WIDE AREA MONITORING AND CONTROL APPLICATIONS

The RTDS synchrophasor technology based WAMCS setup can be used for various monitoring and control applications such as,

- Linear state estimation
- Wide are angle stability monitoring and control
- Wide area voltage stability monitoring and control
- Adaptive protection
- Emergency control
- Model validation, etc.

This work has focused on following two specific applications.

A. *Real Time Voltage Stability Monitoring*

Several methods [8] based on use of P-V or Q-V curves at load buses, singular/eigen value analysis of power flow or system jacobian, bifurcation analysis, various stability indices, etc., have been used for offline analysis of voltage stability monitoring of power systems. With the use of synchrophasor technology, it has become possible to monitor the system voltage stability online and initiate preventive controls, if the incipient voltage instability can be predicted in advance. Huang *et al.* [9] have suggested dynamic L-index for online prediction of the voltage stability. The L-index can be computed at each load bus (say bus-j) using the following equation:

$$L_j = \left|1+\frac{V_{0j}}{V_j}\right| \qquad (1)$$

where,

$$V_{0j} = -\sum_{i\in G} F_{ji}V_i \qquad (2)$$

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \qquad (3)$$

V_i is the *i*th generator bus voltage, G is the set of all the generator buses, F_{ji} is the ji^{th} element of the F_{LG} sub matrix of (3), V_L, I_L are the voltage and current vectors at the load buses, V_G, I_G are the voltage and current vectors at the generator buses.

The other potential index for voltage stability monitoring is the Voltage Collapse Proximity Index (VCPI) suggested by Raghunatha *et al* [10]. At a load bus-j, VCPI can be defined as:

$$VCPI_j = \frac{\left|V_{cg} - V_j\right|}{\left|V_j\right|} \qquad (4)$$

where,

$$V_{cg} = \frac{\sum_{k=1}^{N_G} V_k}{N_G} \qquad (5)$$

V_{cg} is the centroid voltage of the generator bus voltages, V_j is the *j*th bus phasor voltage, N_G is the number of generators, V_k is the *k*th generator bus voltage phasor.

Using the synchrophasor technology, if the PMUs are provided at various buses to measure voltages at a faster rate, the L-index and the VCPI can be computed in real time. Voltage collapse takes place when L_j and $VCPI_j$ reach numerical value of unity.

B. *Wide-Area Robust controller Design*

To damp out small signal oscillations in the system, each generator exciter is provided with Power System Stabilizer (PSS). The conventional PSS (CPSS) is generally tuned individually at a certain operating point and faces the control coordination problem, when put together in the system. A wide area controller can be used to provide supplementary control to CPSS; which must be developed after proper selection of input and output signals and also proper controller design. This work has considered a geometric approach for input and output signal selection [11]. A mixed H2/H∞ output feedback synthesis [12] has been utilized to develop the robust wide area controller. Line active power flows have been considered as the input set.

To design the controller, the nonlinear power system has been linearized at nominal operating point. As the size of the controller so obtained, is equal to the size of the system plus the size of the weighting functions, the model of the system has been reduced using the multiplicative error balanced model reduction techniques, otherwise, difficult to implement. A short description about the model reduction is given below.

Let G(s) be the transfer function of the original nth order system and $G_k(s)$ be the order of kth order system, then, in balanced stochastic model truncation, it satisfies the following relation:

$$\left\|G^{-1}(G-G_k)\right\|_\infty \le \prod_{k+1}^{n}(1+2\sigma_r(\sqrt{1+\sigma_r^2}+\sigma_r))-1 \qquad (6)$$

where, σ_r is the rth Hankel singular value of G(s) and can be determined by, $\sigma_r = \sqrt{\lambda_r(\boldsymbol{LM})}$, λ_r is the rth eigenvalue of ($\boldsymbol{LM}$), where, $\boldsymbol{L}$, $\boldsymbol{M}$ are the solution of Lyapunov equations:

$$\boldsymbol{LA}^T + \boldsymbol{LA} + \boldsymbol{BB}^T = 0 \qquad (7)$$

$$\boldsymbol{MA} + \boldsymbol{A}^T\boldsymbol{M} + \boldsymbol{C}^T\boldsymbol{C} = 0 \qquad (8)$$

To design the centralized wide-area controller the weights chosen are based on the trial and error approach. The weighting functions for the three systems are obtained as given below:

$$W_1(s) = \frac{400}{(s+12)} \;,\quad W_2(s) = .7 \;\text{ and }\; W_3(s) = \frac{10s}{(s+400)} \qquad (9)$$

Where, $W_1(s)$ is a low pass filter in the H_2 performance channel for out-put disturbance rejection, $W_2(s)$ is a high pass filter or constant in the H_2 performance channel to reduce control effort and $W_3(s)$ is a high pass filter in the H_∞ performance channel to provide robustness against model uncertainties.

V. SIMULATIONS

To demonstrate the capabilities of the real time digital simulator facility, two cases were simulated using wide area data. Description of the two cases and its results are as follows.

A. *Case I*

WECC 9-bus test system [13], shown in Fig.6, is considered to monitor the voltage stability of the system. This system contains 9 buses, 3 generators, 3 transformers and 6 transmission lines. In this case, it is assumed that PMUs are available at 3 generator terminals and one sensitive load bus, identified based on dQ/dV sensitivity analysis [14]. The case is simulated by increasing the load at the rate of 10% of base case per 20 sec. In this case stability monitoring is performed by using the two voltage stability indices, L-index [9] and VCPI [10]. The results were monitored by using the meters available in the runtime environment of the RTDS (Fig. 7) and also by exporting the results at every operating point to external application (Fig. 8). Both the indices reach to numerical value 1 as the system moves towards the stability limit. The results observed in Figs. 7-8 are matching with the results reported in [9] and [10].

B. *Case II*

The New England 39-bus test system [15] shown in Fig.9, is considered to demonstrate the wide-area robust damping controller (WARDC). This system consists of 10-generators and each generator is assumed to be provided with governors, AVR and IEEE ST1A type static exciter. The loads in the system are assumed to be constant impedance type. A WARDC for generators G3, G5 G9, and G10 is designed by taking active power flow in the lines connecting buses 8-9, 4-5, 16-19, 17-27, 2-26 as input. The system is simulated in RTDS/RSCAD environment.

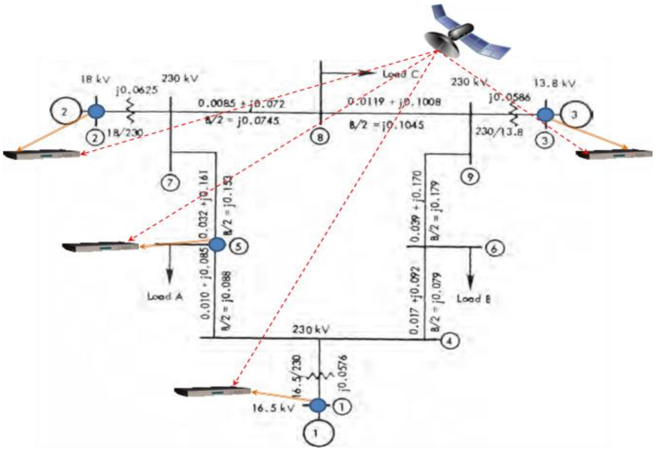

Fig. 6: WECC 9 bus test system

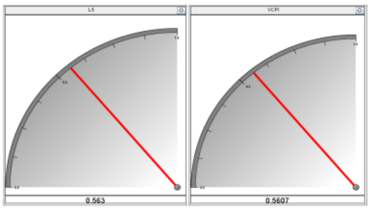

Fig. 7: L-index and VCPI at 140% above the base case in the RTDS run-time environment

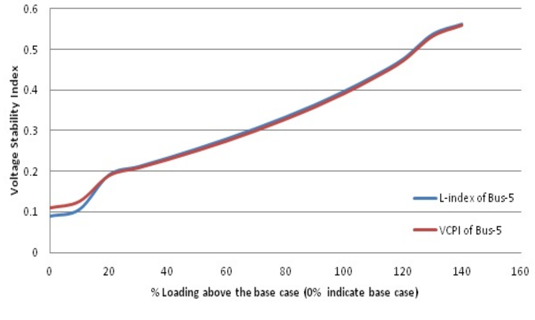

Fig. 8: Voltage stability indices monitored using external application

For the non-linear simulation, a 3-phase fault has been applied at bus 3. The circuit breakers are assumed to clear the fault at bus-3 after 100ms, and permanently open the line 3-4 after 110ms. The response of the system to WARDC is shown in Figs. 10-12. The results show that, without any wide-area controller present in the system, the oscillations persist up to 14 sec, however, by applying the wide-area control signal, the oscillations have been damped out in 10sec. There is also a marginal improvement in 1st overshoot and undershoot of the response by applying the centralized wide-area controller.

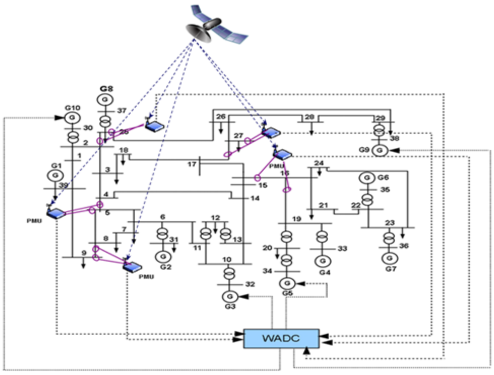

Fig. 9: New England 39-bus test system

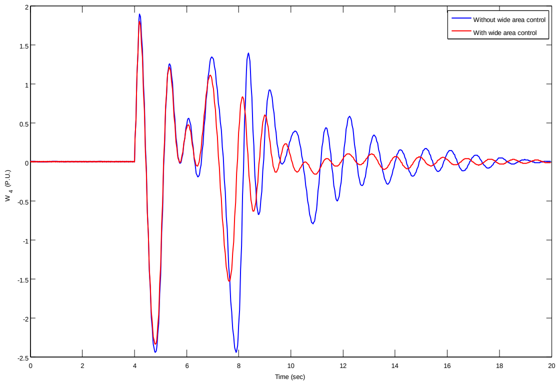

Fig. 10: Speed deviation of generator 4

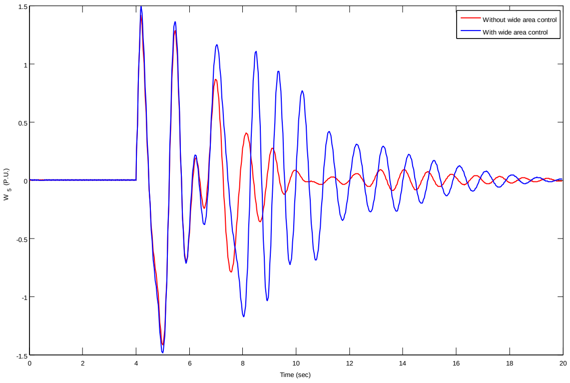

Fig. 11: Speed deviation of generator 5

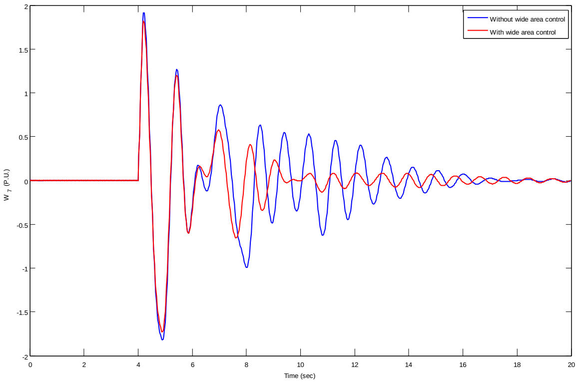

Fig. 12: Speed deviation of generator 7

VI. CONCLUSION

This paper reports the development of lab scale WAMCS using real time digital simulation facility at IIT Kanpur. The importance and effectiveness of the real time digital simulation is demonstrated with the help of two simulation studies.

Power system voltage stability can be assessed in real time by calculating the voltage stability indices in RTDS with the help of phasor data available from the PMUs. The computation of L index and VCPI using RTDS, demonstrated in this paper, can be extended to large practical power systems for monitoring and control purpose.

The parameters of the wide area controller are also designed and validated using the real time simulation. The tuning of wide area controller for stability study has been able to achieve better transient response after fault inception as compared to that without the wide area control. The RTDS enables the user to validate the controller during severe conditions, which would not be possible to test in a physical power system.

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