Real-Time simulation of monitoring security in the Mexican Power System

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***Abstract*--In this paper, the authors propose an analysis tool for information exchange and security assessment suitable for a Power system operated from a control center. The basic idea of the proposal consists of exchanging information between an OPAL-RT simulator and a PC running on-line in an open loop. The RT simulator creates power system signals and the PC uses this information to feed an OPF program which evaluates load-generation contingencies. The framework has been planned with the Mexican dispatch, which is not presently an open energy market and the operators at the control center have authority to handle security control over the whole network. The OPF algorithm comprises a solution of the unit commitment problem as well as an hourly transmission security check including such network constraints such as line flow, voltage magnitude and reactive power limits. An AGC model is included in the Unit Commitment algorithm. The method for security assessment is demonstrated on a simulation of one control center of Mexican power grid surrounded by regional areas and supervised by one national center.**

***Keywords*: Security assessment, Contingencies, Optimal Power Flow, Real-Time simulation, OPAL–RT platform.**

I. Introduction

REAL–TIME simulation has been traditionally used for hardware-in-the-loop applications of protection and control systems [1-3]. However, the current state-of-the-art of power system simulation presents opportunities for applications in security analysis, where real-time simulator can provide solutions to complex problems in accelerated time. In this context, the performance of the simulator is based on how many contingencies can be analyzed in a minimum amount of time. In this paper we shall demonstrate the use of a fully digital real-time simulator for the development of a security analysis tool for use in the control center of a power system.

It is well known that the enormous amount of data flowing from the SCADA systems, particularly in times of emergencies, can be overwhelming for the system operators [4].

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Furthermore, crucial decisions have to be made in a very short time. Consequently the operators must rely heavily on alarms, which only provide information confined to a small area and can lead only to local solutions. This can mask potentially dangerous developing situations, such as voltage collapse, equipment overloads, and lower stability margins. Real-time simulation can offer some relief, by reducing and prioritizing the data to a more manageable level, such that decisions of a more global nature can be made. However the usefulness of these simulators is limited by the accuracy of the data with which they are provided.

Off-line studies have traditionally been used for contingency analysis, these studies comprising, for example, load flow which help to establish limits and restrictions on key equipment [5, 6]. However, these studies normally do not use real-time data, and they have to wait until the state estimator provides updates. Consequently RTSA based on outdated data cannot be used to reliably assess contingency options in a state of emergency and operators have to rely on their experience.

In this paper, we propose a real-time interchange of data between the power system and an optimal power flow program running in real time as a step towards providing a reliable evaluation of optimal contingencies in the event of an emergency. This fast and accurate supply of data for operators will help towards assessing the wide area effect of their actions.

We demonstrate this approach by using a real-time simulator to provide a real-time model of part of the Mexican power system. An AGC is also implemented in the model and monitors the inter-area power flow. Data from this model is transferred to a PC running an OPF program [7]. The model is provided with unit commitment and load forecasting data, and a load-change or a unit-commitment change is provided to the real-time simulator. The OPF responds by providing the latest load flow, and which results in a real-time security assessment, comprising, for example, new warnings and restrictions, such as line and/or machine overloads, prospective voltage collapse, etc.

II. Real Time Security Assessment Simulator

Figure 1 shows an overview of the real-time security assessment simulation. An OPAL-RT simulator (shown on the left) simulates the power system is in real time. The node voltages and currents are converted to phasors by a simulated PMU, which are then fed to a PC (shown on the right).

Both computers share a topology data base. The hourly unit commitments and the load forecasts are stored in a data base which feeds the real-time simulator.

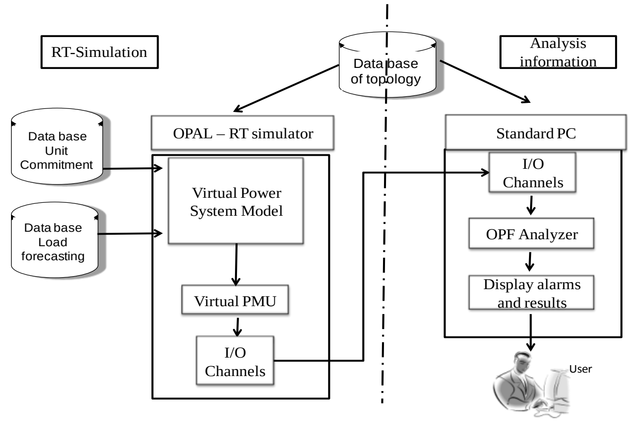

Fig. 1 Overview of static security assessment

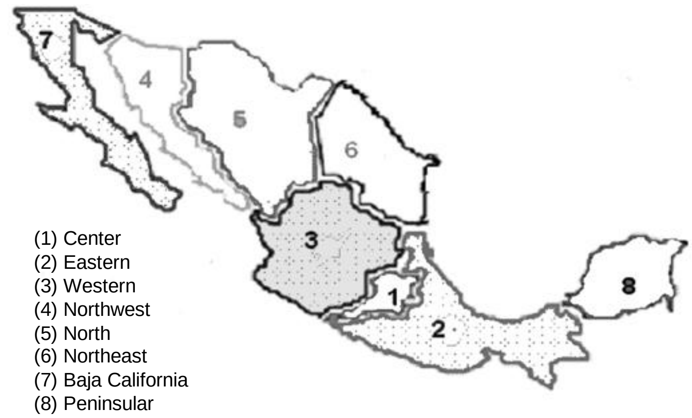

Fig. 2 Distribution of regional control centers in Mexico

The state equations of the simulated power system are:

$$\dot{x} = A\tilde{x} + B\tilde{u}. \quad (1)$$

Where the states are in the vector $\dot{x}$ and $\tilde{u}$ comprise the sources. The OPF analyzer, simulated in the PC, rather than using detailed models is based on the following steady-state representation:

$$V^* \, Y \, V = (P - jQ) \quad (2)$$

where Y is the admittance matrix and V is the vector of nodal voltages. The current is represented indirectly in terms of complex power $S=P+jQ$.

The OPAL-RT dynamic power system representation is organized as hierarchical subsystems:

a) The Master Subsystem contains machine models and local controls.

b) A Slave Subsystem which represent 400 KV lines and loads.

c) A Slave Subsystem which runs an AGC.

d) A Console Subsystem which provides outputs to send to the OPF analyzer.

The OPAL-RT simulator also performs local signal processing, converting the time-domain nodal voltages and currents to phasors (virtual PMU). The output signals from the PMU are exported to the PC through the real-time simulator I/Os.

The second computer, a standard PC, is running the OPF and receives the signals from the real-time simulator via its own I/Os. Effectively the system is running in open loop.

A. Preparation For Distributed RT Execution

Figure 2 shows a map of Mexico and the regional control areas established for operating the National Electric Power system. The system operates under hierarchical control, where the National Control Center (CENAL) is the highest hierarchical authority and supervises a second level for eight control centers.

CENAL verifies with the control centers the values of real power specified by the Unit Commitment study. To keep the security of the whole interconnection at a desired level, a fast evaluation is required at every control center.

Our study focuses on region 3. This control center is responsible for thirty-four machines. Eight inter-area transmission lines connect four neighboring regions.

For our studies we will consider the most important plants, comprising sixteen thermal units and nine hydraulic units. The 400 kV systems comprise twenty-three nodes.

The one-day Unit Commitments and Load Forecasting for Control Center 3 were determined in advance of the actual study. Device switching, such as capacitors and reactors, were not considered.

B. Real-time System Simulation

The configuration of the Master computation subsystem block, Slave blocks and Console block are shown in Figure 3. The Master Subsystem block is connected to Slave Subsystems through three 400 kV transmission line blocks: MND, PIT, LCP; and these lines provide the time delays for the parallelization of the model onto three CPUs.

Figure 4 illustrates the configuration network of region 3 in figure 2. This topology was configured as show in figure 3.

All three-phase currents and voltages from the 400 kV nodes go through signal processing to extract their phasor values based on a four period moving window. The RT simulator uses a common global time, consequently the phasors are correctly synchronized and we can consider them as PMU [8, 9], which implies that we have a virtual SCADA system.

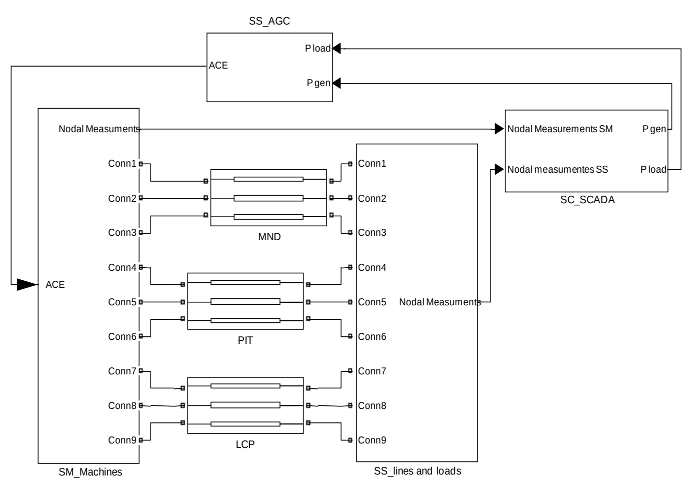

Fig. 3 Subsystem models for execution in RT simulation

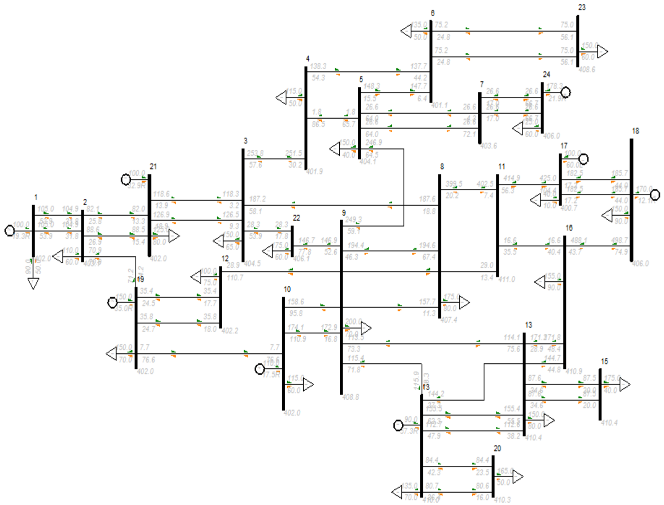

Fig. 4 Power System configuration of region 3

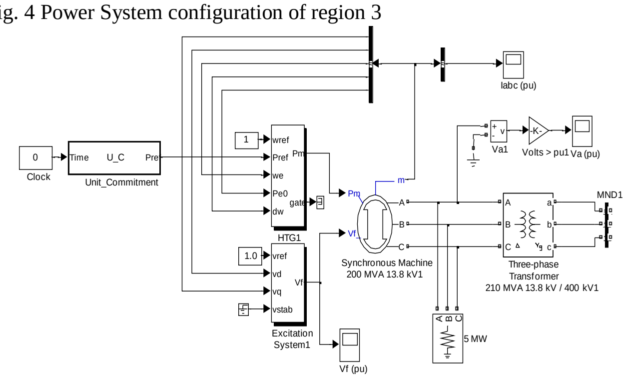

Fig. 5 Model configurations of thermal units

Figure 5 illustrates the synchronous machine model. It includes both local and remote controls, comprising the local PSS and exciter, as well as the remote AGC.

The block located at the left side of the illustration comprises a MatLab-Function which provides a power input as function of time (unit commitment) [10]. This input is corresponds to a mechanical energy which corresponds to the electric power required by the Unit Commitment. All synchronous machines are provided with a 24-hour commitment schedule.

C. Unit Commitment algorithm

Figure 6 shows a typical day performance registered in a control center. The total power committed by the units should ideally be the same as the real power consumed by the customers. The total load of consumers P_{load}, is obtained from a short term load forecasting study [11].

$$P_{load} = \sum_{i=1}^{N} P_i \tag{3}$$

where P_i is the power contribution of each one of N machines to be dispatched.

Figure 6 may also be used towards determining possible start-up and shut-down times of the units towards minimizing operating cost and satisfying various constraints [12-14]. In practice the start-up of one *i*-machine (after synchronization) requires initial conditions related to real power consumption. The effect on transient stability resulting from the connection of the machine is not studied in detail at this stage of the project.

We only considered N machines in the RT simulation and we changed values of power P_i, by means of the schedule or by the AGC.

To get our schedule, we have a MatLab algorithm to determine the power mechanical input to the N permanent machines. Figure 7 shows the flow diagram used to acquire a 24 hours schedule of Unit Commitment. Every hour λ is used as a power reference [11].

The left side illustrates our routine to minimize error and at the same time consider cost of production. In this manner, the integrated power calculated would be optimal with respect to the requirements of economic dispatch.

Recall that, as shown in Figure 1, there are two separate data bases corresponding to the load forecasting and the unit commitment.

Load demand of power systems is random in nature, but we have calculated values of λ to characterize this phenomenon for the control center 3 in Figure 2. Our RT dynamic program can also deal with faults on transmission lines and the response of the system protection.

We can change parameters of simulation systems including fault location, fault resistance, fault time, and fault type, etc. The RT simulation has the capacity to change settings and values; however we are not doing that at this stage. It is assumed that network topology is unchangeable.

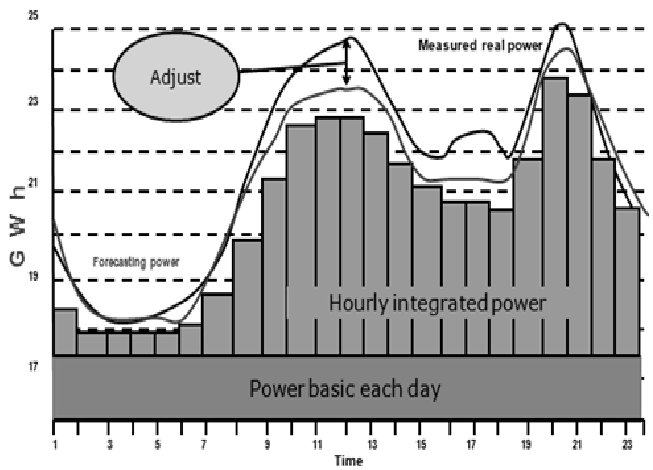

Fig. 6 One day load performance and hourly Unit Commitment

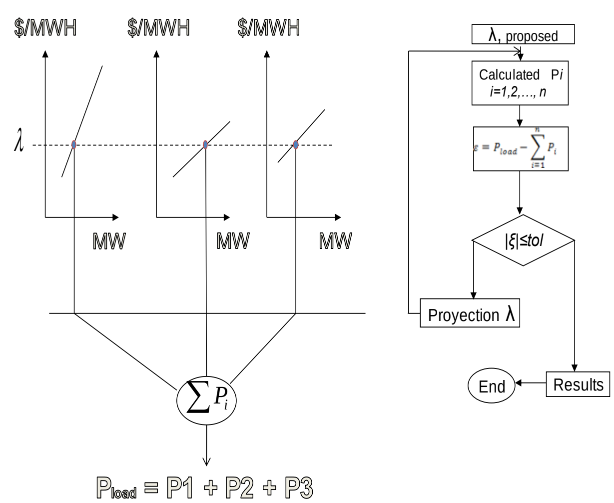

Fig. 7 Flow chart to obtain Unit Commitment

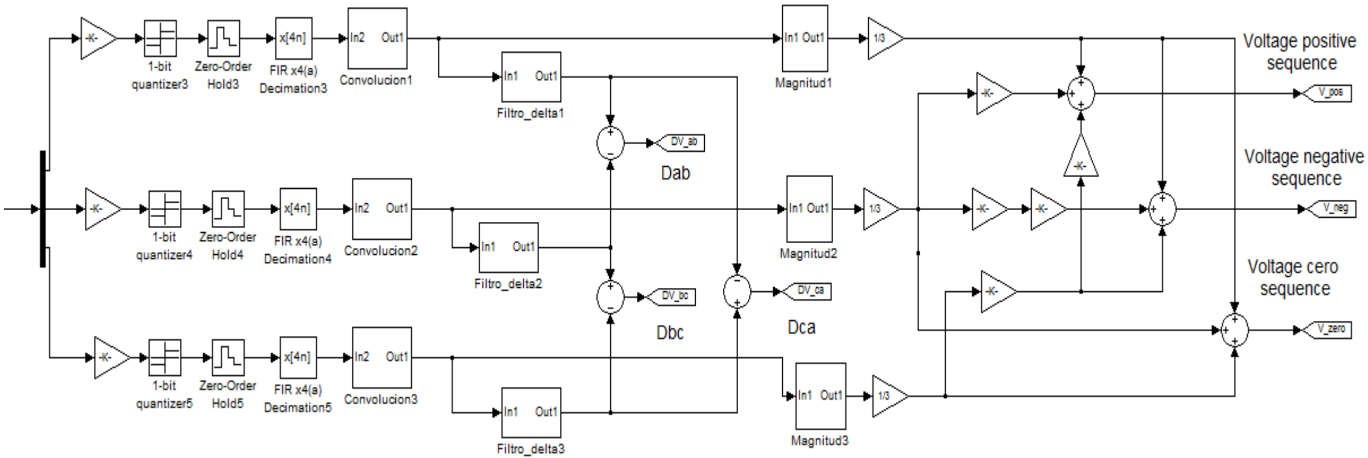

Fig. 8 SimPowerSystem Block set Model to obtain phasors

D. *AGC Model*

Considerable work has been done on modeling and designing an AGC [15]. The conventional approach to the design of an AGC involves construction of dynamic models, using measurements from the interconnected grid, generator units, and their local controls.

A theoretical solution to the national power system is to share real-time SCADA information to run our security assessment. Our AGC model aims at maintaining the inter-area power flow. For our simulation the swing bus is located at the receiving-end of the inter-area transmission lines. The voltage-current relationship from infinite buses is limited through a restriction.

An extra input at P_i commitment generators allows an adjustment range of 1-3%. The simulation will wait for 10 min until returning the area control error (ACE) to zero.

The AGC correction starts after a load alteration and when it is recognized ACE as described by:

$$\mathrm{ACE} = \left(\sum \mathrm{P}_{\mathrm{ITL}_8} + \sum_{i=1}^{N} \mathrm{Pi}\right) - \left(\sum \mathrm{P}_{\mathrm{load}}\right) \quad (4)$$

Where $\left(\sum \mathrm{P}_{\mathrm{ITL}_8}\right)$ refer to eight inter-area transmission lines in the model and $(\sum \mathrm{P}_{\mathrm{load}})$ is the total load demand at the control center. This simple AGC model is not suitable for small signal perturbations, however for long term simulations, the performance is acceptable.

E. *Digital Signal Processing and the Data Acquisition*

The real-time simulator solves in the time domain and in our simulation the nodal voltages and currents are converted to phasors using a digital signal processing algorithm, as follows:

1.-The nodal voltages and currents pass through a second order Butterworth Anti-aliasing Filter (FAA).

2.-The output from FAA is digitized using 16 samples per cycle. The digitized samples are then convoluted with the coefficients of a Cosine Filter. The result of this convolution provides the positive sequence nodal voltages and currents. Figure 8 shows our model.

3.-The signals are multiplexed and exported to the OPF Analyzer.

For wide area monitoring, the PMU becomes a key element to align outputs by means of a reliable Global Positioning System (GPS) clock [9]. With these models we use a time tag, so that outputs are time aligned in a virtual SCADA system. The state estimator is absent in this security assessment tool.

F. *OPF Analyzer*

A standard optimal power flow (OPF) was implemented to run off-line on the PC shown in Figure 1. System data from the real-time simulator is exported to the OPF program described above, our data exporter immediately updates. While this is a simulation, in a real system the data would come from the RTU's, as shown Figure 9.

The Unit Commitment and Load Forecasting schedules, provided through a MatLab function, control the start-up and shut-down of loads and/or generators. The maximum allowable power transfer for a certain transmission line is set with respect to thermal capacity, angular stability or voltage stability.

To identify risk or constraints violations on the control center, the following must be verified:

1. Each generator is operating in a range greater than a specified minimum power, and less than its maximum power design limit:

$$\mathrm{P}_{\min}\, i \leq \mathrm{P}i \leq \mathrm{P}_{\max}\, i \quad (5)$$

2. The node voltages are within the range established by a voltage stability study:

$$|\mathrm{V}|_{\min}\, i \leq |\mathrm{V}|i \leq |\mathrm{V}|_{\max}\, i \quad (6)$$

3. The reactive power at each node is limited between minimum and maximum values:

$$\mathrm{Q}_{\min}\, i \leq \mathrm{Q}\, i \leq \mathrm{Q}_{\max}\, i \quad (7)$$

4. The apparent power flow on each of the transmission lines is limited to a maximum value:

$$\mathrm{S}i \leq \mathrm{S}_{\max}\, i \quad (8)$$

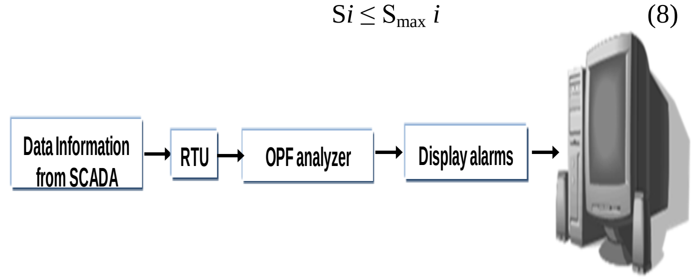

Fig. 9 OPF analyzer diagram

Furthermore, if the control devices cannot alleviate violations, optimal power flow or constrained economic dispatch based on unit commitment will have no solutions owing to excessive transmission flows or violation of voltage constraints, etc.

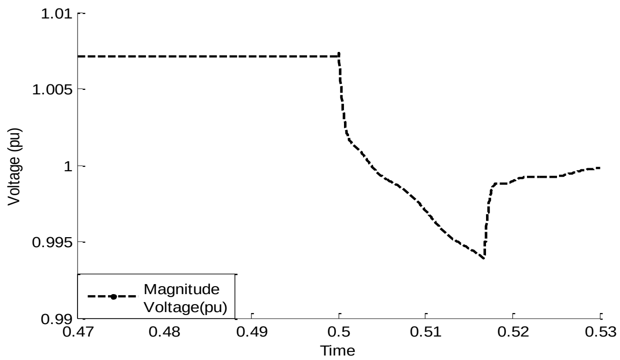

Fig. 10 a) Calculated Phasor voltage

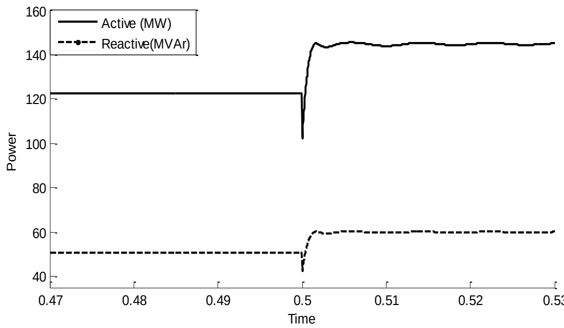

Fig. 10 b) Active and Reactive Power

III. Test Case of Real-Time Studies and Results

A security assessment study was performed on the network shown in Figure 4 (simulated on the OPAL-RT simulator), where load and generation conditions were simulated during a 24 hour period. An extract of the Unit Commitment data is shown in Appendix A, and the one-day load behavior is given in Appendix B.

A change of load was simulated at node 8 in figure 4, and corresponding waveforms at that bus is shown in Figure 10. Figure 10a shows positive sequence voltage after signal processing to extract the phasor data, where the processing was performed using 16 samples per cycle. Figure 10b shows in the upper side the simulation of active power during load change, and lower in Figure 11a shows the corresponding lagging reactive power.

The figure 11b shows the nodal voltages for the entire control center during one day, and the right side shows the signals corresponding to the active power consumed at twelve of the load nodes. The results clearly show that the Node 8 requires reactive power support. Note that at this stage we have not included switching contingencies – this will be added in the future.

Note also that the time signals are synchronized, as would be the case with PMU registers.

The OPF program runs simultaneously on the PC in order to determine violations of constraints on devices. This on-line application would allow the system operator to monitor security, providing warnings whenever the system goes to alert or emergency state under load or generation contingencies. The response requirements (time and reliability) are higher for emergency control actions and our system will assist the operator through providing wide-area information. Consider, for example a security assessment performed on our simulated network at noon.

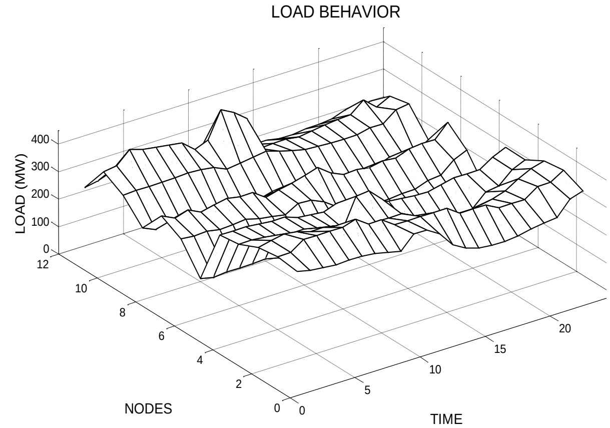

Fig. 11 a) Load power consumed at the principal power system simulation

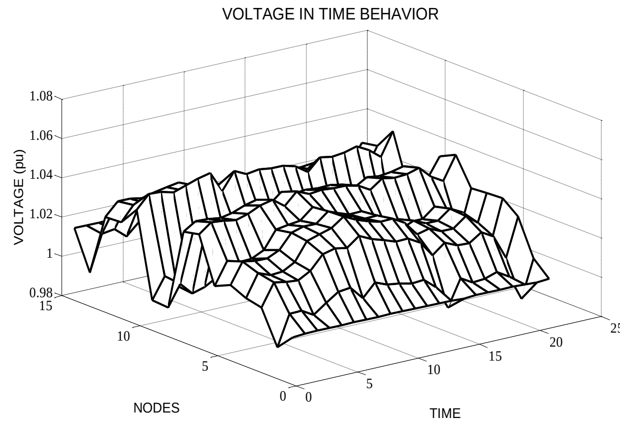

Fig. 11 b) Node voltages determined by the real-time

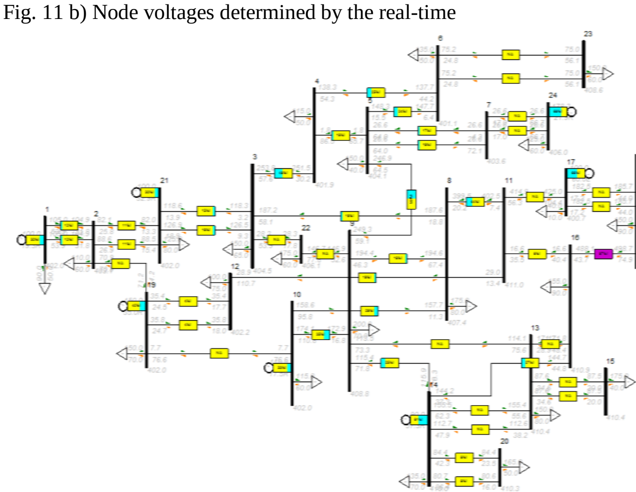

Fig. 12 On-line solution to security assessment of power system

Figure 12 illustrates the global behavior seen at the control center. The colors indicate the operating condition of each element: green indicates a state of normal operation, yellow indicates a state of operation near the limit set for the device, magenta indicates an item that is in violation of these constraints, and red indicates an overload and impending disconnection. This visual representation is part of the strategy to detect risky conditions over a wide area, towards implementing suitable control actions.

Another advantage of the use of real time simulation is the enhancement of the contingency list, allowing more contingencies to be solved in a shorter time.

IV. CONCLUSIONS

This paper has presented the use of a real-time simulator for implementation of improved strategies in power system security assessment. In the on-line mode the real time system data is fed an OPF, which determines limits and restricted conditions. The benefits of using a combined RT simulator and OPF program include:

1. wide-area on-line solution of security assessment even for very large networks,
2. an improved visualization of the overall state of the network,
3. global security assessment rather than local.

The virtual PMU's used to feed system data to the OPF provides information can be used for different applications such as wide area protection, emergency control and system optimization.

Future work will include:

1. Applying an AGC model for small signal perturbations,
2. fault contingencies and switching devices as reactors or capacitors,
3. adaptation of a close loop approach,
4. evaluation of the effect on transient stability resulting from the connection of machines,
5. dynamic security analysis.

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APPENDIX A

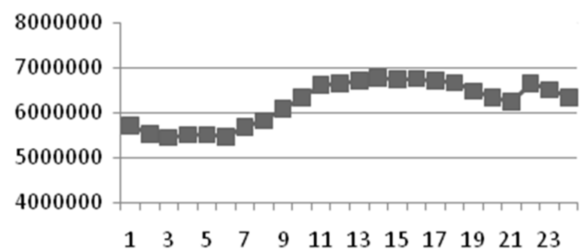
ONE DAY SCHEDULE OF UNIT COMMITMENT

	HOURS																								
Units	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**Total**
1	280	280	280	280	280	280	280	286	280	280	280	290	290	290	280	280	280	290	280	290	280	290	290	290	**6806**
2	248	250	236	230	230	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	**5944**
3	300	300	280	280	280	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	**7140**
4	270	270	270	250	250	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	**6440**
5	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	**8400**
6	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	**8400**
7	82	88	80	80	80	89	120	120	120	120	120	120	120	120	120	120	120	120	120	120	117	120	120	120	**2656**
8	118	120	104	81	81	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	**2784**

Note: shows the number of generating units by itself and not for placement on the bus, this is because CFE prohibits the disclosure of information by a confidentiality agreement he signed the author of this paper.

APPENDIX B

LOAD FORECAST FOR A SUMMER DAY (24 HOURS) WITHIN THE CONTROL CENTER 3



APPENDIX C

LIST OF ACRONYMS

AGC	Automatic Generation Control
SCADA	Supervisory Control and Data Acquisition
PMU	Phasor Measurement Unit
FAA	Antialiasing Filter
CFE	Federal Electricity Commission
RTSA	Real-Time security assessment
OPF	Optimal Power Flow

BIOGRAPHIES

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Laurence A. Snider, He was a Visiting Professor in the Electrical Engineering and Computer Science Department, Tulane University, New Orleans, USA. He is currently a Visiting Distinguished Professor in the Graduate program of Electrical Engineering, University of Guadalajara, Mexico. His general research interests are in the areas of real-time power system simulation, application of power electronics in power transmission and distribution systems, power quality, and high voltage engineering and insulation coordination.