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An Advanced Training Simulator for Synchrophasor Applications

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SUMMARY

Recently there has been a rapid growth of phasor measurement unit (PMU) deployments worldwide - PMUs provide time-tagged synchrophasor grid measurements at a sub-second rate. In step with PMU growth, there has been a growth of new synchrophasor applications which use the PMU data. Today, control centers are deploying "PMU Measurement-Based" analytics that augment the traditional "Model-Based" EMS analytics [1].

Operators have been trained on SCADA and EMS functions with dispatcher training simulators (DTS) for decades.

This paper describes an advanced training simulator (ATS) that facilitates operator training with the new synchrophasor applications. This will pave the path towards winning operator acceptance of these applications. Operator trust is required for migration into the production control room, for real-time monitoring and decision making.

KEYWORDS

PMU, Synchrophasor, Training Simulator, Operator Training, Transient Stability

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INTRODUCTION

The traditional Dispatcher Training Simulator (DTS) has been adequate for SCADA-based EMS applications and has served its purpose since the 1980s. With the introduction of time-synchronized measurements (such as, Phasor Measurement Units or PMUs) as part of smart grid initiatives worldwide, conventional operator training tools need to be revisited [2, 3, 5]. The traditional DTS is not suited for training operators with sub-second PMU-based analytics. These PMU analytics are 'model-free' – their model is the actual power system.

The Advanced Training Simulator (ATS) described in this paper, provides an offline environment for operator training in the new PMU analytics. ATS leverages the existing, user-familiar infrastructure of the traditional DTS platform.

ATS simulates PMU data at every bus in the EMS database (e.g. all 6,000 buses of a production EMS model) and will be able to export it in the IEEE C37.118 format – this is exactly the same format as data from real PMUs in the field. The ATS provides a large scale, system-wide PMU streaming data source, for training on PMU analytics.

LEVERAGING THE EXISTING DTS INFASTRUCTURE FOR THE NEW STABILITY ENGINE

The existing DTS infrastructure forms the basis of the ATS. The fundamental difference is that the power system simulation engine is replaced with a transient stability simulation engine. The stability engine requires dynamic power system data. ATS uses a Transient Security Assessment Tool as the stability engine (from now on referred to as TSAT) [6]. Stability results include: voltages, angles, frequencies. These results will be exported as simulated PMU data in IEEE 37.118 format, to the EMS Phasor Data Concentrator (PDC).

Figure 1 shows a functional overview of the ATS. ATS replaces the 'uniform frequency' long-term dynamic simulation engine of the traditional DTS, with a short-term transient stability simulation engine, that simulates inter-unit dynamics at a sub-second rate. DTS is implemented with a long-term simulation (LTS) engine, and ATS is implemented with the LTS augmented with a short-term simulation (STS) engine. The incremental work required to deploy ATS at the EMS, is to add the dynamic model data for all the generators in the EMS DTS model. The dynamic model is mapped to the EMS node circuit breaker by using a translation table for individual generators, whose purpose is to include the short term model data provided by the planning engineers. The DTS is capable of simulating wind, hydro, gas turbine, thermal etc. Additionally user defined models (UDM) can be created, if needed.

ATS provides positive-sequence voltages and currents, and frequencies at sub-second rates. These are well-suited for operator training on the PMU-based analytics at the EMS. ATS does not provide three phase currents and voltages or instantaneous phasor data.

PMU to PDC data exchange has been successfully tested with offline file transfers. We are currently developing the capability to export TSAT results in IEEE 37.118 format. This feature is under test, and the enhanced TSAT product is scheduled for release soon.

BENEFITS OF A SOFTWARE TRAINING SIMULATOR

ATS is a software simulator. The ATS common code-set is easily configurable to model different utility EMS grids and model sizes. The code-set can be configured for as small as a 10 bus test model, or as large as a 6,000 bus production EMS model. This model configuration takes less than a day to set-up. The ATS uses the exactly the same EMS model, and can be initialized from the real-time EMS with a single key-click. Customers need to only provide a PSS/E or PSLF file for the dynamic model. A CIM data file requires preparation from the customer and import development for use in the

ATS. ATS generates simulated PMU data at every single bus in the model. Also, ATS can run in parallel to, and independent of, the EMS.

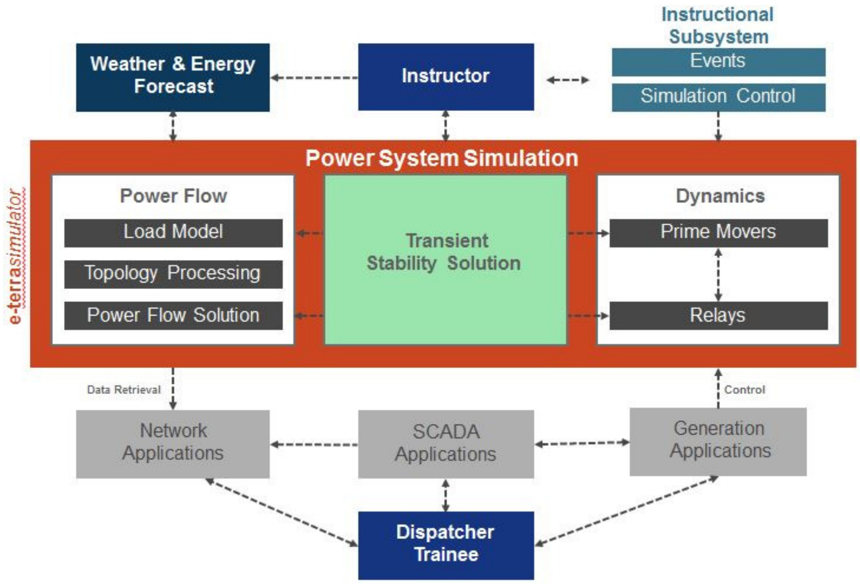

Figure 1: ATS - Functional Overview

FUNCTIONAL REQUIREMENTS

ATS requirements include:

- Capable of providing transient system responses, after system disturbances, and/or switching/protection actions in the form of positive sequence quantities.
- Capable of simulating power system models in close to real time, with a system size of around 6,000 buses. The outputs will be streamed to the long-term model at real time speed, with possible short pauses at the simulation discontinuity points (system initialization, disturbance/switching/protection action points).
- Capable of handling common power system models, including network, generators (including renewables) and their controls, loads, SVC/STATCOM, HVDC, transformer tap changer, etc.
- Capable of handling models for extended term simulations such as AGC.
- Capable of performing simulations continuously for at least 20 seconds or until the transient is damped.
- A feature to force the stability simulation to converge more quickly to the post-disturbance state.

SHORT-TERM TIME DOMAIN SIMULATION

The TSAT engine that is embedded in the existing DTS long-term simulation (LTS) environment is the STS, as shown in Figure 1. The ATS Master display is shown in Figure 2. The LTS and STS processes communicate every second using TCP/IP, to synchronize model states.

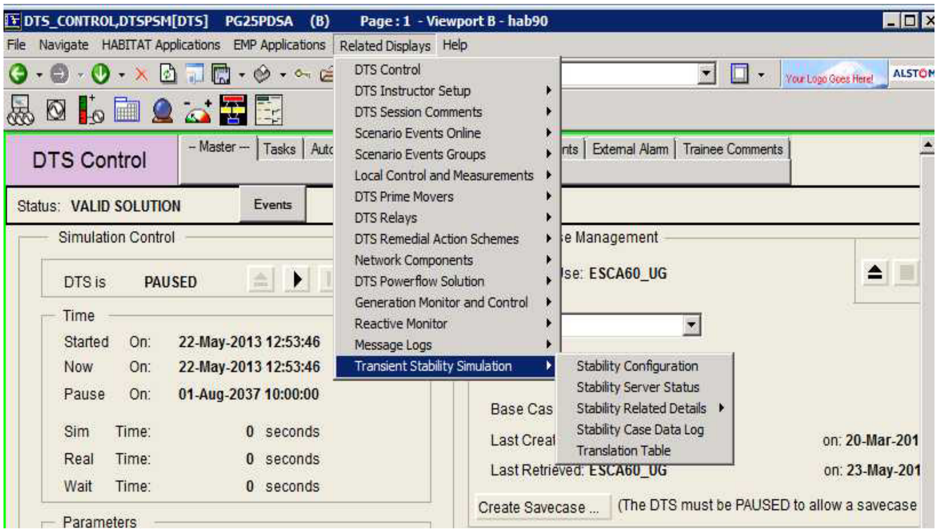

Figure 2: ATS - Master Display

ATS features include:

- **Power Flow and Dynamic Initialization**: LTS prepares a power flow case for a specific system condition.
- **Faults and Outages**: During training simulations, the ATS instructor initiates special event types (such as Outages and Faults) which automatically invokes STS.
- **Measurements and Signals**: Pre-defined output quantities (monitored variables at PMU locations) are streamed to the LTS. The STS provides data at 30-60 samples/second.
- **Relay Actions**: TSAT has the capability to simulate relay actions and SPS - for instance overcurrent and impedance relays, for out of step conditions. It can simulate load shed based on under voltage or under frequency conditions. During the STS, the LTS concurrently continually monitors the network state and informs STS when new LTS voltage/frequency/current relays have been triggered.
- **STS to LTS handoff**: STS notifies LTS when to assume or relinquish simulation control. An immediate handoff can also be manually triggered, such as when an LTS relay trips.
- **Expediting the STS to LTS handoff**: If STS oscillations are damping out, an additional artificial damping factor can be used, to bring STS system conditions more quickly back to uniform frequency. Figure 3 shows an example where a 20 second transient stability simulation has been reduced to about 14 seconds.

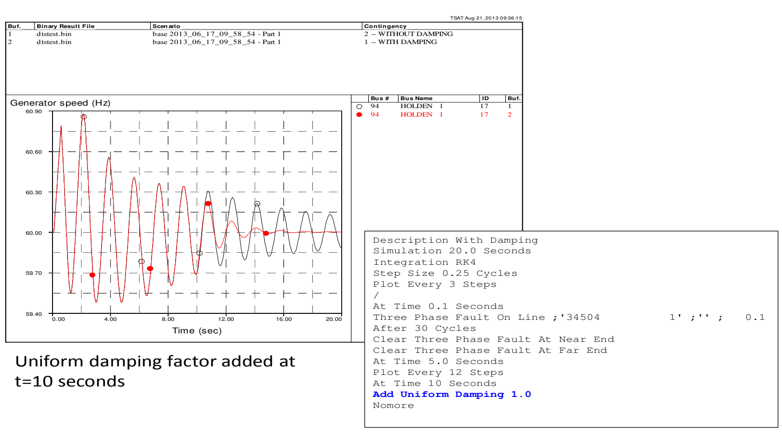

Figure 3: TSAT Model Enhancements

SCADA OPERATOR ACTIONS AND EVENTS

Figure 4 shows the addition of the new STS event definitions in the DTS Instructor's Events system. These include:

- New "transient stability events"
- Existing long-term DTS events can be interpreted as transient stability events
- New switching events that occur during the STS

The different types of transient stability events include:

- Single-, Double- and Three-phase faults to ground - at a bus or on a line. If the fault is associated with a line, the percent distance along the line should be provided from the bus terminal.
- Clearing of faults to ground at a bus
- Clearing of faults to ground at the near end or far end of a line
- Time delays are part of the switching file - to simulate breaker actions as well as relay actions. This is indicated by the number of cycles before the trip.

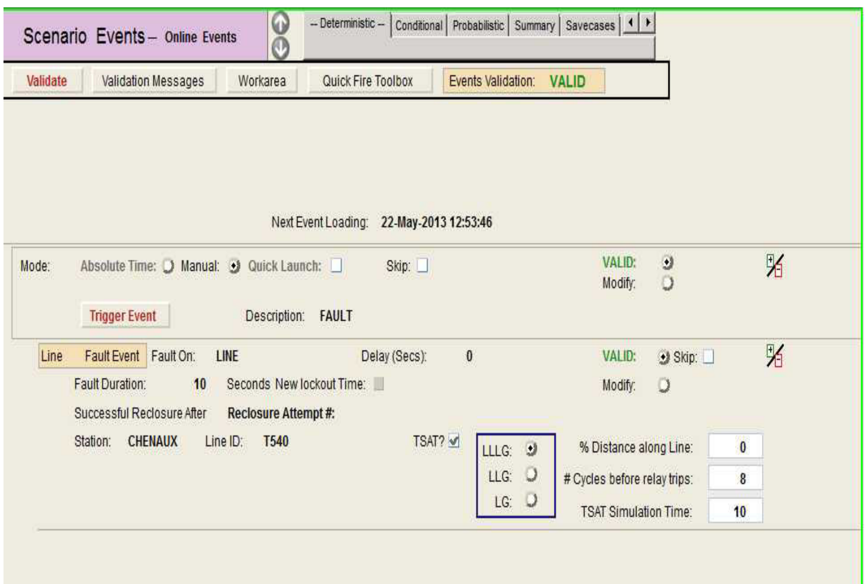

Figure 4: Defining STS Faults and Events

The following types of transient stability events are included in the Instructor's Event definition system:

- Outage of a bus and/or a Line
- Outage of Load and/or Generation

An optional engineering flag is added to force the system to converge more quickly to from the stability simulation to the long-term simulation:

- Add uniform damping – Yes/No

Some events are created on the "fly", just like any other LTS event. Figure 4 shows user input parameters to simulate a disturbance event for training. The figure shows the type of fault, the fault duration, number of reclosure attempts, and the pre-disturbance conditions. The results of the transient stability simulation are stored and available for further analysis using TSAT's native visualization tools.

The PMU measurement types and locations are entered as monitored variables in TSAT. The PMU locations are defined as part of the network modelling function. Signals are specified as either SCADA (a sample every one or four seconds) or PMU (a sub-second rate). STS provides complex voltage, complex current, complex power, and filtered bus frequency signals for any component in the network model.

- PMU measurements are specified as monitored variables, these can be reviewed and plotted for post-event analysis
- The PMU sampling resolution is the user-defined, STS integration time-step.

SUBSECOND PMU DATA STREAMS

ATS will be capable of creating PMU data streams in the IEEE C37.118 protocol to the PDC. This PDC data drives the PMU-based applications, such as: disturbance detection, oscillation monitoring, monitoring angle differences, islanding and resynchronization, etc. The following types of STS PMU measurements are available:

- Frequency and Frequency Rate of Change
- Bus Voltage Magnitude and Angle
- Branch Current Magnitude and Angle

Figures 5 and 6 shows short-term stability results due to a disturbance. These are output as sub-second PMU simulated data.

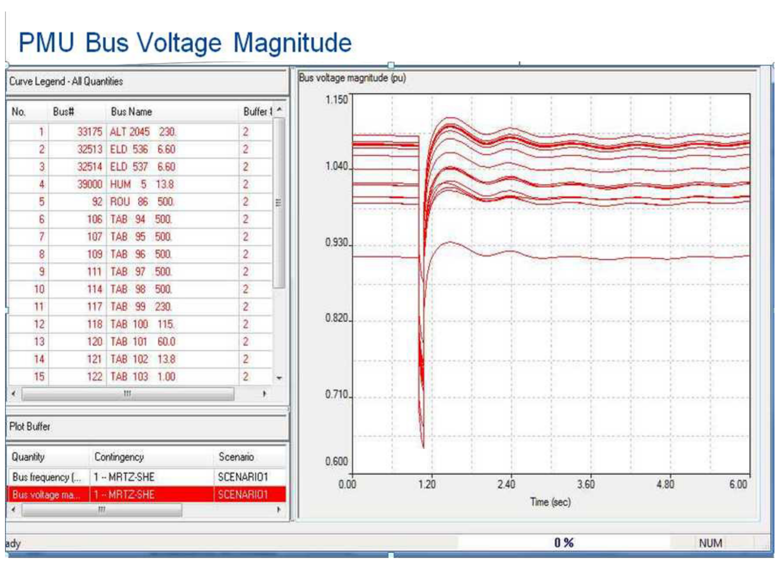

Figure 5: Voltage Magnitude Measurements

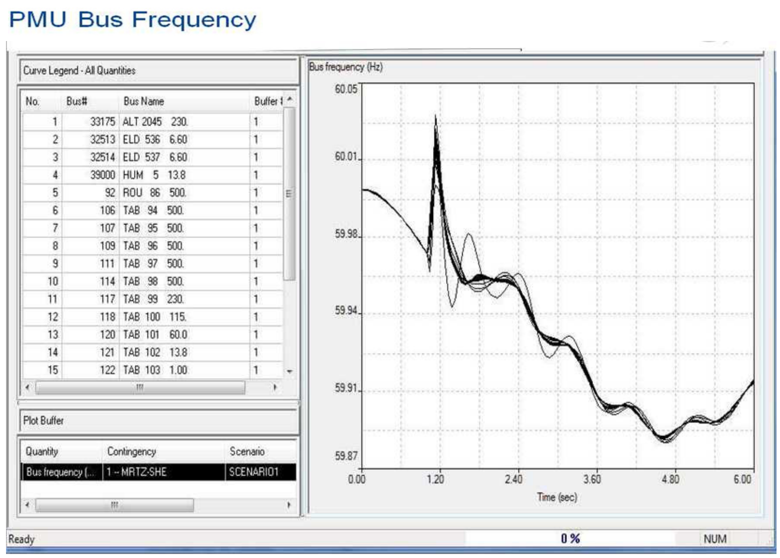

Figure 6: Frequency Measurements

ONE SECOND DATA STREAM

System frequency is calculated at the one second cycle in the LTS. This is the time when the LTS and STS processes are synchronized, by exchanging:

- Bus Frequency
- Generator Mechanical power
- Voltage Magnitude and Angle
- Branch Current Magnitude and Angle
- Bus Frequency and Frequency Rate of change
- TSAT Solution Status

LONG-TERM NETWORK STATE UPDATE AT THE END OF THE DISTURBANCE

The STS also provides the final power flow solution, at the end of the transient stability simulation. STS insures that there are no system oscillations; a pre-condition for a steady-state power flow solution. The following information is provided at the end of the STS:

- Bus Voltage Magnitude
- Bus Voltage Angle
- Generator Power -MW/MVAR
- Load - MW/MVAR
- Performances indices which assess the goodness of the STS

Using the above information, the base case LTS power flow is solved, and LTS continues as it would in the traditional DTS.

UNIFIED FRAMEWORK – ATS, EMS DSA, PHASORPOINT

Figure 7 is an overview of the EMS model-based and the measurement-based analytics. The model-based analytics are existing EMS SCADA applications and dynamic security assessment tools (VSAT and TSAT). The measurement-based analytics are the PMU-based analytics (called Phasorpoint) which rely on the simulated PMU data from the PDC. ATS provides both the simulated SCADA data (from LTS) and the simulated PMU data (from STS).

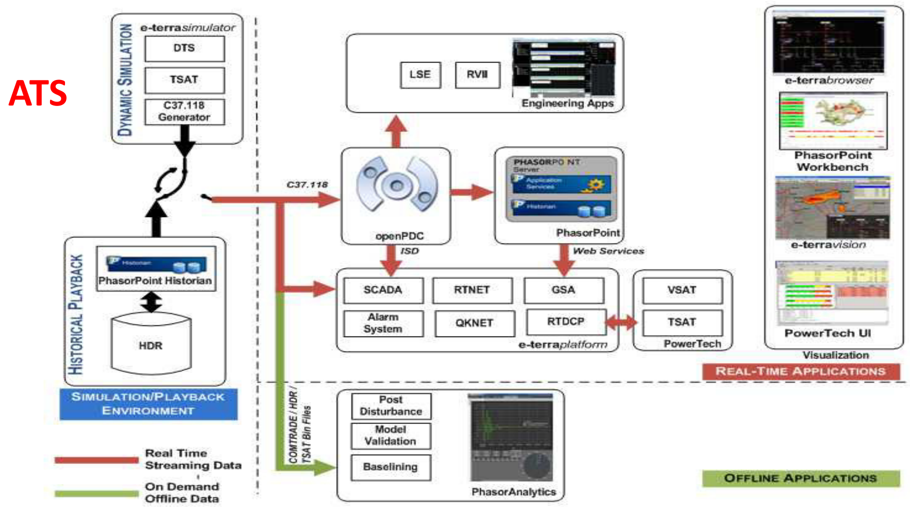

Figure 7 Unified ATS with Model-Based and Measurement-Based applications

The simulated PMU data from STS will be provided to the PDC in the IEEE 37.118 format. The PDC is the data source for the PMU-based analytics.

The following the model-based and measurement-based EMS analytics, that use the ATS output:

- LSE- linear state estimator - performs substation data validation by combining network model information and PMU data;
- RVII- real-time voltage instability indicator - a PMU-based real time voltage instability indicator application, which predicts the proximity of the current operating point to voltage collapse.
- Phasorpoint- Oscillation monitoring, monitoring angle differences, disturbance detection, etc.
- RTNET- is the EMS state estimation - enhanced with PMU measurements.
- QKNET- a SCADA/PMU based application which runs at the SCADA rate, and shows a geographical view of the system state and topology changes.
- RTDCP- a model-based online application that provides the data to the model-based VSAT and TSAT tools. These tools calculate transfer limits for specific paths.
- Advanced Visualization- provides the geo-spatial view of oscillations, voltage and frequency problems and alarms, as well as SCADA related measurements and EMS results.
    - One can drill down into the native UI of VSAT/TSAT and Phasorpoint analytics, as needed.

The next phase of the ATS will include a Historical Playback environment and will use previously stored SCADA (traditional HDR) data, along with PMU data.

REALTIME OPERATIONS TRAINING

ATS has been deployed at Pacific Gas & Electric in San Ramon, CA. This project is partially funded by the US Department of Energy as part of the Smart Grid Invest Grants. This is a test facility that will be fully operational in 2014, and its advanced functionality is in transition to the production EMS.

An "integrated" training environment for familiarizing PG&E's operations staff with synchrophasor applications alongside traditional EMS functions has been identified as a crucial component for an effective training program.

ATS is a vehicle to help operations personnel gain a deeper understanding of how to monitor and control the grid under their jurisdiction. More and more utilities are adopting Wide Area Management Systems (WAMS) as an effective method of understanding the impact of system events, the dynamic behavior of the grid and potential mitigation strategies.

In North America for example, the NERC certified System Operators who operate the grid, will need to master these new concepts. Familiarity with concepts of voltage-angle differences and oscillatory stability will be required to assess grid performance in real time. The widespread introduction of PMU-based high speed real-time measurements of current and voltage requires that we move these concepts from the experimental stage to the real-time production environment.

ATS permits operators to observe dynamic grid phenomena in a training environment that closely mimics the real-time environment. The operating engineers and dispatchers can develop scenarios that closely resemble actual events. At the same time, they learn interactively, to develop best practices on how to mitigate potential threats to the grid.

The PMU sub-second data is available in virtually real-time [4]. These are also available to the EMS at a one second rate for State estimation. Phasorpoint in Figure 7 uses sub-second PMU data to monitor and detect oscillations; these results are subsequently available for display at the EMS at a one second rate. Sub-second PMU data are also used by the linear state estimation - LSE - to perform state estimation at the substation level. The next version of ATS will be capable of retrieving stored data from the PDC and SCADA to initialize new training sessions. Figure 7 also shows the interface to a Simulation Playback environment.

Trainers using ATS can demonstrate to system operator trainees, how to analyze the stress on congested paths or interconnections as voltage-angle changes, for different loading and system configurations. The impact of loss of large of loads or generators can also be demonstrated. System operators can test – hands on – various methods of voltage control in the wake of heavy system loading or loss of transmission facilities.

One of the powerful features of ATS is its capability to aid in development of restoration guidelines, as required by NERC, in response to major system outages. System operator training in this critical area is essential to operation of the power grid. ATS can be used to blackout the system and then to have the operator step through the sequential actions manually, to gradually restore the system, region by region.

ATS can also be an essential tool in raising the level of understanding for WAMS-based automated controls.

CONCLUSIONS

The traditional DTS has been adequate for SCADA-based EMS applications. It has served its purpose since the 1980s, but is not suitable for testing the new sub-second PMU-based analytics. The new Advanced Training Simulator, ATS, implements a transient stability engine for simulating the power system behavior, during transient disturbances.

The ATS provides simulated PMU data at every bus in the EMS database, and will be able to export the data in the IEEE C37.118 format to the EMS PDC. The PDC will then provide PMU data streams to the PMU-based analytics at the EMS.

To summarize, the ATS is an easily scalable, easily configurable, software solution, which provides simulated PMU streaming data for the entire EMS network model, which can be used for operator training with WAMS analytics at the control center.

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