Latest Simulation Technologies for Improving Reliability of Electric Power Systems

Kiyoshi Segawa
Yasuo Takahashi
Shinichi Higuchi
Takamitsu Hae
Yasushi Tomita
Takashi Nishi, Dr. Eng.

OVERVIEW: Thermal and nuclear power plants are key products in the electric power sector and there is a demand to improve their generation efficiency and maintain reliability. Meanwhile, with the expectation that more renewable energy capacity will be connected to the grid, there is also a need to implement smart grids that can provide electric power reliably and economically. In addition to experimental demonstration, Hitachi, in its research and development of these products, has been proactive in adopting numerical simulation techniques for simulating actual plant operating conditions or transient situations, and is working to put them into practical use.

INTRODUCTION

IMPROVING the efficiency of power generation equipment and ensuring its reliability are the most important factors in maintaining the reliable supply of electric power on which the infrastructure of society depends. In preparation for greater adoption of renewable energy in the future, it is also essential to establish technologies for connecting this additional generation capacity to the grid.

This article describes the latest simulation techniques used as a preliminary to experimental testing in the research and development of Hitachi's main products for the electric power sector, namely steam turbines, gas turbines, generators, and smart grids.

STEAM TURBINE SIMULATION

The latest ultra super critical steam turbines expand steam at high temperature and pressure (main inlet steam pressure of 25 MPa and main steam temperature of 600°C) to a 5-kPa vacuum at the condenser. Because two-phase flow (wet steam) occurs in the low-pressure latter stages of the turbine due to moisture resulting from non-equilibrium condensation, techniques are required that use CFD (computational fluid dynamics) to analyze the compressible steam in a way that takes account of these steam properties. Another phenomenon specific to steam turbines is the reverse flow that occurs in the low-pressure latter stages at low flow rates and high back pressure. Reverse flow increases excitation forces and has a major impact on turbine blade reliability. Assessing the excitation force is also important for ensuring reliability, and this requires flow simulation techniques that can solve three-dimensional unsteady flow phenomena quickly.

Hitachi has been using numerical simulation techniques to ensure reliability as well as for performance improvement, and has developed its own technology to suit these different objectives. These programs developed in-house are used in conjunction with commercial software in the design of actual products after being subject to validation including thorough element and turbine experiments.

The following section describes the results of applying techniques for steady and unsteady flow simulations to steam turbine test facilities.

High-pressure Turbines

Advances in numerical analysis and faster computers have made it possible to conduct comparatively rapid evaluations of the flow patterns

Fig. 1—Steam Turbine Test Facility.
The test facility can be used to conduct performance and reliability testing of the high-pressure stage of steam turbines.

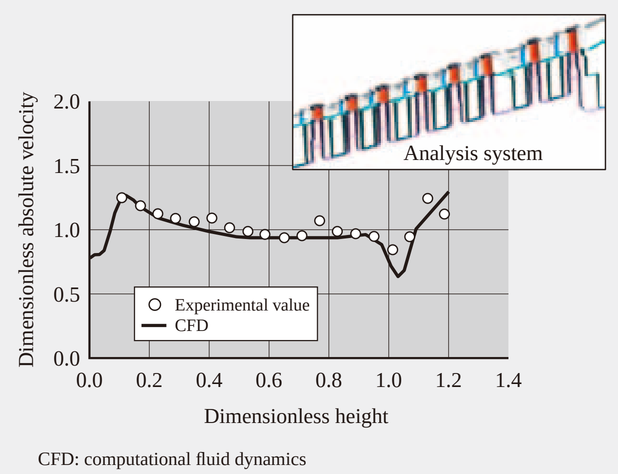

Fig. 2—Results of Three-dimensional Analysis of Multi-stage Steam Flow (CFD Analysis).
The results show good agreement between analysis and experiment at the multi-stage outlet.

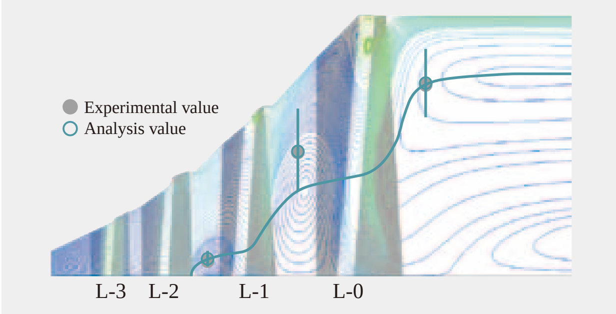

Fig. 3—Results of Quasi-three-dimensional Multi-stage Unsteady Analysis.
The blue line in the figure shows the maximum height of the reverse flow region of the average flow field, the black dots show the experimental values, the blue dots show the time-averages for the maximum reverse flow height at each time calculated by the analysis, and the vertical lines indicate the standard deviation.

and other performance factors of multi-stage turbines like those used as high-pressure turbines. It is important to verify the accuracy with which turbine performance and other factors, such as the flow pattern at the outlet of the final stage, can be predicted for a given multi-stage turbine configuration and inlet and outlet boundary conditions. Fig. 1 shows the test facility for the high-pressure stages of steam turbines, which is used to validate analysis techniques, and Fig. 2 shows the results of a three-dimensional analysis of multi-stage steam flow (CFD analysis).

The analysis system assumes the same configuration as the test facility shown in Fig. 1 and includes a nozzle diaphragm and a seal for the rotor blade tips. Because a comparison of the three-dimensional, multi-stage CFD analysis with experimental results indicates a high level of prediction accuracy for the flow pattern and other performance factors, the technique is also being applied to the design of actual products.

Low-pressure Turbines

As described above, reverse flow can occur in the latter stages of low-pressure turbines if the mass-flow drops under low flow rate and high outlet steam pressure conditions. In addition to reducing the turbine load, this also spreads to the upstream stages. Hitachi has conducted quasi-three-dimensional multi-stage unsteady analyses of the low-load flow field and compared the results with experimental measurements of reverse flow. Fig. 3 shows analysis results of average flow field (in the form of trajectory lines) for a very low load (5%) case[1]. Analysis and experiment show good agreement for the reverse flow region, indicating that the reverse flow across multiple stages at very low load can be analyzed with good accuracy. A comparison with experimental results also shows that the analysis can accurately simulate the amplitude of pressure fluctuations at the flow path endwall under different load conditions. In this way, it is possible to study the excitation effects that the flow has on the turbine blades and produce designs that ensure reliability by using quasi-three-dimensional multi-stage unsteady analysis to provide an accurate assessment of unsteady flow fields at low load.

GAS TURBINE SIMULATION

Analysis of All Compressor Stages

A gas turbine is a turbomachine consisting of stationary stator vanes and rotor blades that rotate along with the compressor and turbine. Fig. 4 shows a cutaway photograph of the Hitachi H-25 gas turbine. The flow of air into the axial compressor of the H-25 gas turbine exceeds the speed of sound in the initial-stage rotor blades at the compressor inlet. Meanwhile, the flow inside the compressor decreases in speed and increases in pressure to 1.5 MPa at the outlet. Because the flow through the rotor blades in this type of multi-stage axial compressor is highly three dimensional, three-dimensional turbulence analysis is needed to design an arrangement of blades able to deliver both performance and reliability.

Because the inlet Mach number is greater than one at the transonic blades in the upstream part of the compressor, it is important to predict the position of the shock wave that occurs on the blade suction

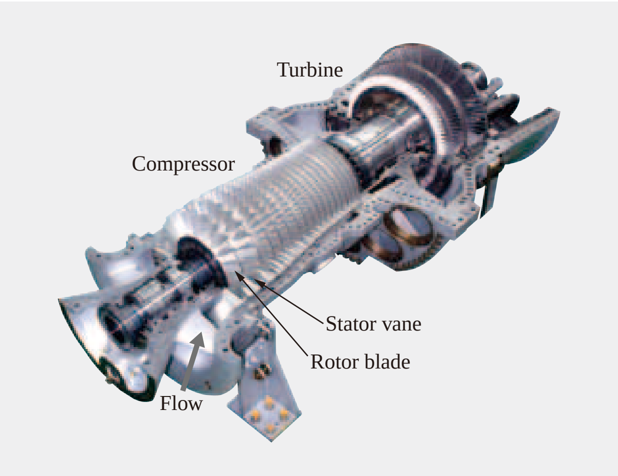

Fig. 4—Hitachi H-25 Gas Turbine.
This cutaway photograph shows the H-25 gas turbine casing and rotor.

surface and the shock wave loss that occurs due to interference at the blade surface boundary layer. The subsonic blades at the downstream part of the compressor are designed with a shorter blade length and low aspect ratio and the flow is predominantly secondary due to the formation of an endwall boundary layer. Accordingly, a method is required that can analyze the flow between each set of blades three dimensionally and predict the secondary flow loss with high accuracy. As a multi-stage axial compressor consists of a number of sets of rotating blades and stationary vanes located along the flow direction, it is important that the analysis match the flows between each of these.

As the previous design technique used a quasi-three-dimensional flow analysis to estimate the performance of all stages of the axial compressor, the effect of the three-dimensional characteristics of the flow depended on the modeling. Also, as three-dimensional CFD analysis also splits the compressor analysis into multiple stages, the accurate prediction of the endwall boundary layers is an important factor in the analysis of the latter stage flow fields.

The improved performance, faster speeds, and greater capacities of computers in recent years mean it is now possible to conduct steady-flow analyses of all stages of an axial compressor. Fig. 5 shows the results of such an analysis. The calculation model used in the analysis has a computational grid with approximately 14 million points. The turbulent flow model used in the analysis is an SST (shear stress transport) model which is regarded as being highly accurate. By using a model that considers the tip clearance between the rotor blades and stator vanes and the axial air flow for the turbine blade cooling air and seal air in the intermediate stages, the analysis is able to reproduce the actual operating conditions with high accuracy. Although modeling of the actual situation, including a turbulent flow model and the boundary conditions between the rotor blades and stator vanes, is necessary, it has reached a level that allows highly accurate numerical simulations to be performed with a prediction error of 1% or less between experimental measurements and CFD-based calculations of the flow field for the entire compressor.

Simulation techniques are essential for making further improvements to compressor performance and reliability. Hitachi is working on research and development of optimized design software for three-dimensional blades that incorporates an optimization algorithm into the CFD calculation for the purpose of reducing the losses in the compressor blades. Use of this optimization software in the design of three-dimensional blades has succeeded in reducing the shock wave loss of transonic blades and the secondary flow loss of subsonic blades[2]. Hitachi is also combining validation by flow analysis and unit testing to produce more advanced simulation techniques. This article describes an example of steady-flow analysis of a compressor. Other important topics in compressor research include the study of phenomena such as rotational stalling at startup and unsteady flow under partial load. These require coordinated and coupled analysis that combines both flow and structural analysis techniques.

For the future, Hitachi intends to continue improving its simulation techniques in preparation for a time when large simulations that perform unsteady analysis of entire compressors or gas turbines will be possible.

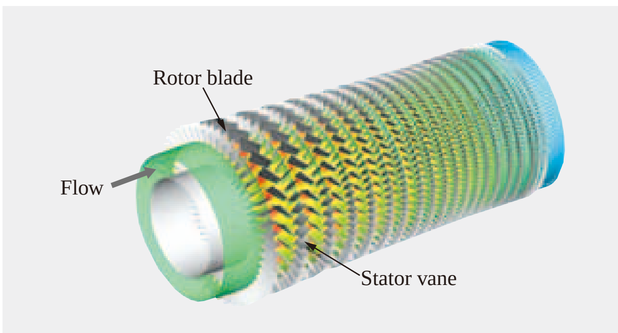

Fig. 5—Analysis of Multistage Axial Compressor.
The contour lines indicate the isentropic Mach number distribution around the compressor blades.

Single-stage and All-stage Turbine Analysis

Although gas turbines are turbomachines with multiple turbine stages, just like the steam turbines and compressors described above, their behavior is significantly different due to the use of externally supplied cooling air to cool the blades and endwalls that enclose the gas path. The high temperature of the main stream gas at the turbine inlet (greater than 1,300°C) makes this cooling essential. Typical designs have a flow path formed inside the blade section through which air is passed to carry away the heat from the walls and cool the structure[(3)]. This cooling air is then discharged from holes on the blade surface where it mixes with the main stream gas. In addition to this cooling air, gas turbines also rely on seal air which is deliberately injected so that the hot main stream gas does not get into the gaps that exist in the axial direction between the stator vanes and rotor blades. This seal air also ultimately mixes with the main stream gas.

Some of the air compressed by the compressor, as described in the previous section, is bled off for use as the cooling air and seal air, and the less that is taken the better the thermal efficiency of the gas turbine. Important factors in improving the performance and reliability of a turbine include flow analysis techniques that can model the behavior of the cooling air and seal air as well as the main stream gas, and stress analysis and heat transfer analysis of the turbine structure that comes into contact with these gases. The numerical simulations used in each case require high accuracy. Hitachi is conducting research and development through which it aims to improve the numerical simulations used in design. The following describes one example of this work.

The calculation time and accuracy of three-dimensional steady turbulent flow analysis reached the point where its use in design became practical during the 1990s, and since then the scope of analysis has expanded steadily. The technology is now at a level where a single analysis can be performed for an entire turbine with the only boundary conditions given being those for the turbine inlet and outlet (see Fig. 6). The flow in an actual turbine is unsteady flow as the gas passes from combustor outlet through multiple stages to the diffuser (with each stage consisting of stator vanes and rotor blades), and different analysis conditions are used depending on the purpose of the design. Examples include steady-flow analysis and unsteady analysis of each element, either for one flow path at a time or for the full 360°.

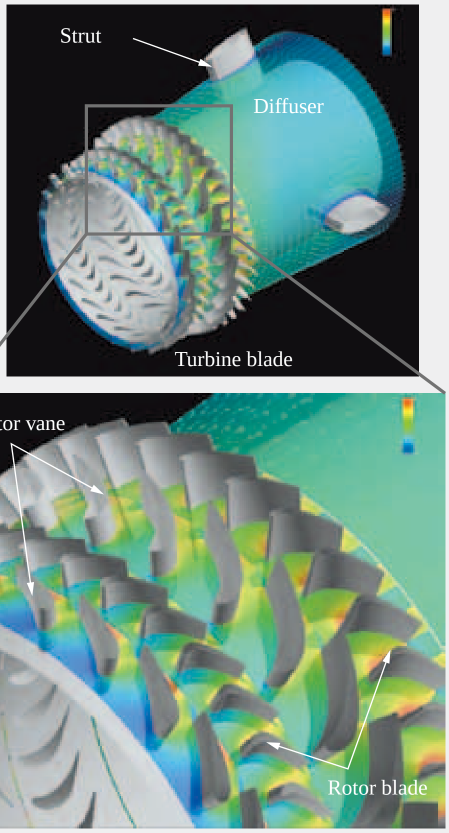

Fig. 6—Analysis of Entire Turbine.
The combined analysis covers the two turbine stages and the diffuser.

For example, steady-flow analyses that can provide quick assessments are used to estimate turbine performance. The mixing of cooling and seal air described above is a phenomenon specific to gas turbines. The total amount of this air is about 20% of the exhaust gas. In addition to modeling how this cooling and seal air mixes, the full-turbine analysis also considers how the physical properties change due to the change in composition that results from this mixing. Whereas analyses conducted in the early days of numerical simulation assumed an ideal gas, this resulted in large deviations from measured values for turbines in particular because the Mach number is influenced by the significant changes in gas temperature due to the large enthalpy drop. This problem was mitigated by making the specific heat a function of temperature, as it is in a real gas. Hitachi has adopted techniques that consider the changes in physical properties caused by changes in the composition of the main stream gas due to the mixing in of cooling and seal air. The improvement in analysis accuracy that this achieves has been confirmed. The benefits of this work are now showing through in research currently being conducted into advanced humid air turbines.

The following describes the use of numerical simulation to evaluate reliability. As described above, cooling is essential to turbine blades and reliability is assessed based on the temperature and stress to which the metal is subjected. The mean values of these can be obtained by using a flow analysis to solve for the main stream gas flow over the exterior of the blades and the cooling air flow inside the blades. These can then be used to calculate the metal surface temperature. In this calculation, an assumed value is used for the heat flux from the gas to the blades. Heat transfer analysis is then used on the blades to obtain this heat flux from the gas. Here, the value used for the temperature at the surface that contacts the gas is the value obtained from the previous flow analysis. The flow and heat transfer analyses are then repeated until the heat flux values converge (heat flux assumed in the flow analysis and heat flux obtained from the heat transfer analysis). The final result is then used as a boundary condition in the stress analysis. This type of analysis, in which multiple phenomena characterized by different governing equations are solved together, is called multi-physics analysis and is expected to play an important role in future designs.

Other ongoing analysis research topics at Hitachi include optimum design techniques and methods for automatically determining the computational grid to use for flow analysis and structural mechanics analysis.

GENERATOR SIMULATION

Development Challenges and Responses

In response to considerations such as growing electricity demand in recent years and protecting the global environment, the requirements for turbine generators include greater capacity, higher efficiency, and smaller size in order to cut costs. Currently, simulation techniques are used in conjunction with experimental testing at each stage of the design and development of turbine generators to evaluate a range of parameters including mechanical strength, vibration, and cooling performance[(4)]. Assessing the cooling performance is important because increasing the capacity and shrinking the size of turbine generators are likely to result in higher heat generation density. The following section describes the use of three-dimensional conjugate heat transfer analysis to estimate cooling performance.

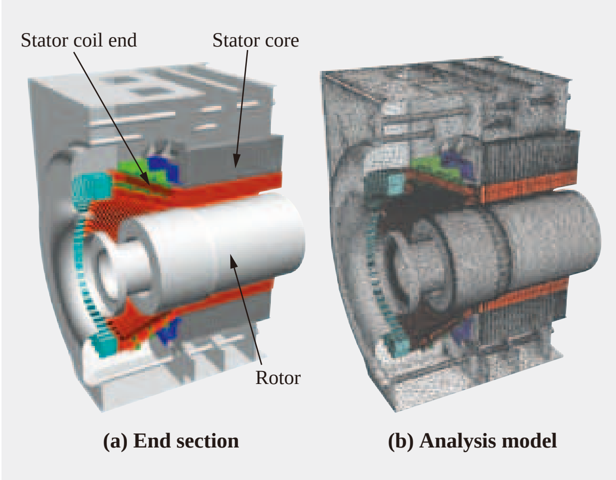

Fig. 7—Turbine Generator End Section and Analysis Model.
The conjugate heat transfer analysis uses a three-dimensional loss distribution obtained by a magnetic field analysis to calculate both the ventilation characteristics and local temperatures.

Three-dimensional Conjugate Heat Transfer Analysis

Coolant gas is circulated inside turbine generators to remove the heat produced by electrical and mechanical losses. The flow of this coolant gas is made more complex in the end section of a turbine generator (see Fig. 7) by the presence of components such as the stator coil end and its support plate. Losses also occur in the structural parts of the end section due to magnetic field leakage. Cooling the structural parts of the end section efficiently requires an understanding of the ventilation characteristics and distribution of heat generation in order to estimate the local temperatures. To achieve this, Hitachi has developed a three-dimensional conjugate heat transfer analysis technique for obtaining the fluid and solid temperatures in the end section of a turbine generator.

The analysis model contains the detailed shape of the structural components around the stator coil end to ensure the accuracy of the coolant flow analysis. For the ventilating duct used to cool the interior of the stator core, the analysis model incorporates an empirical formula for the heat transfer coefficient to maintain the accuracy of the temperature calculation and reduce the computational load. To improve the prediction accuracy for the local temperature distribution, the electrical loss used in the analysis model is determined from the three-dimensional loss distribution obtained by a magnetic field analysis of the end section.

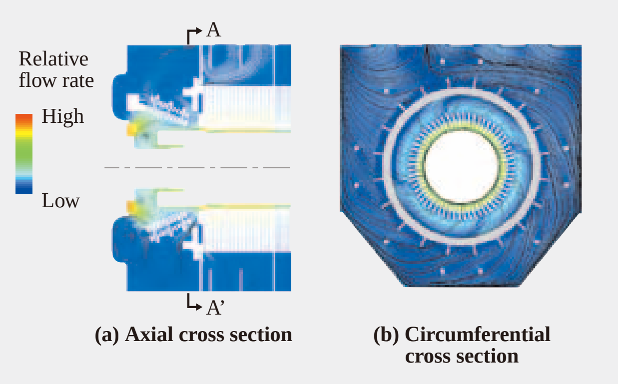

Fig. 8—Flow Rate and Streamline Distribution.
This example shows a detailed analysis of the flow of coolant gas in a turbine generator. The A-A' arrows in the axial cross section (a) indicate the plane of the circumferential cross section (b).

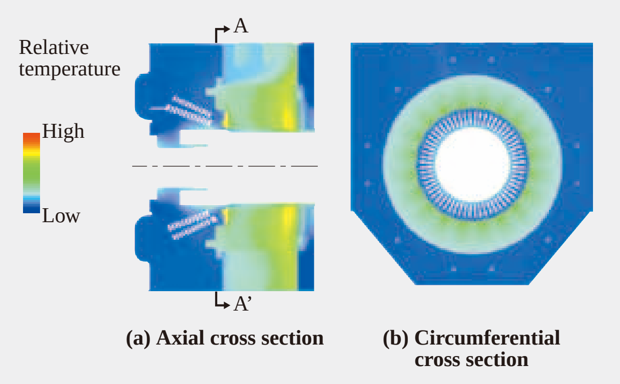

Fig. 9—Temperature Distribution.
This example shows an analysis of the local temperatures in the coolant gas and structural components. The A-A' arrows in the axial cross section (a) indicate the plane of the circumferential cross section (b).

Analysis Results

Performing a three-dimensional conjugate heat transfer analysis of the air-cooled turbine generator provides an understanding of the flow pattern distribution and how it is influenced by the detailed shape of the end section (see Fig. 8). The temperature distribution in both the solid components and the coolant gas can also be obtained by this analysis (see Fig. 9). The analysis results for the structural components and coolant gas temperature have been verified by experimental measurements. Use of this analysis technique makes it possible to estimate the local temperatures taking account of the three-dimensional distribution of losses across the end section of the turbine generator. It also has the potential to allow more precise cooling design calculations.

SMART GRID SIMULATOR

Overview of Smart Grid Simulator

The greater diversity of both power resources and demand means there is a need to implement smart

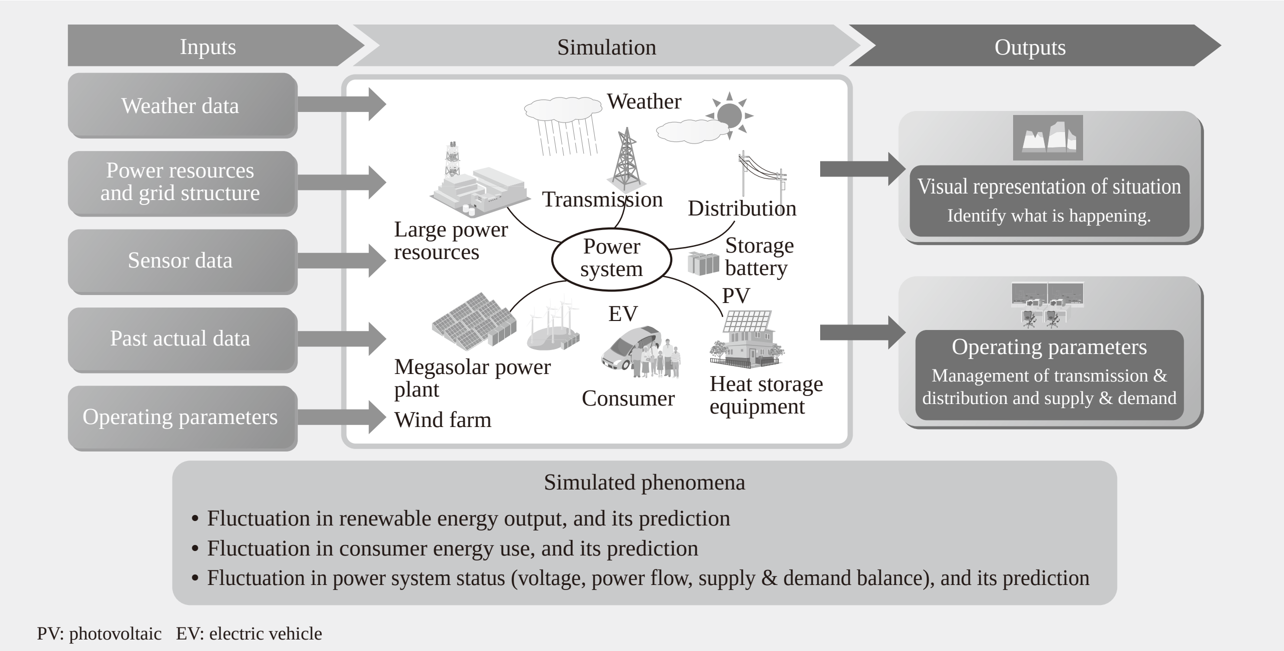

Fig. 10—Overview of Smart Grid Simulator.
The simulator can support activities ranging from planning to operations by simulating the interactions between sites of supply and demand that are likely to occur given the anticipated future diversity in both power resources and demand.

grids that can supply electric power reliably and economically. Examples of this diversity include the connection of more renewable energy capacity to the grid and greater use of electric vehicles. Accordingly, Hitachi has developed a smart grid simulator to provide an engineering environment in which the design and benefits of control systems and other equipment can be analyzed quickly so that timely solutions can be offered.

A plug and play module integration platform was developed for the simulator in which models of the distribution network, voltage regulation equipment, consumer products such as electric water heaters and electric vehicles, photovoltaic power generation systems, consumers, and various control servers are each implemented as separate modules that can be interconnected in a network as required. This allows flexible modeling of different situations and provides a quick way to configure prototypes of new solutions such as systems for analyzing the effect of renewable energy on the power system, voltage stability control, and demand-side management (see Fig. 10).

Example Application

A prototype system for control of local photovoltaic power generation and consumption was developed on the smart grid simulator. Greater adoption of photovoltaic power generation raises concerns about the effect on the power system of excess power and reverse power flow. To deal with this, the proposed control system seeks to direct any excess power from photovoltaic generation systems in its region to local electric water heaters, which can harvest the energy as heat. A feature of the system is that it can maximize overall efficiency and the ability to absorb excess power by controlling how many of the electric water heaters in a group of houses to operate so as to achieve the optimum outcome based on factors such as their efficiency and hot water demand.

The prototype consists of a power flow module that calculates the voltages, currents, and other “state values” at various points in the distribution network; a consumer module that models things like the output of the photovoltaic generation systems, the heat output and power consumption of the electric water heaters, and the consumer consumption of power and hot water; a weather module which produces random weather scenario data; a demand-side management control server module that generates plans for the production and consumption of heat in the electric water heaters for the group of houses; and a main module that coordinates all of the other modules.

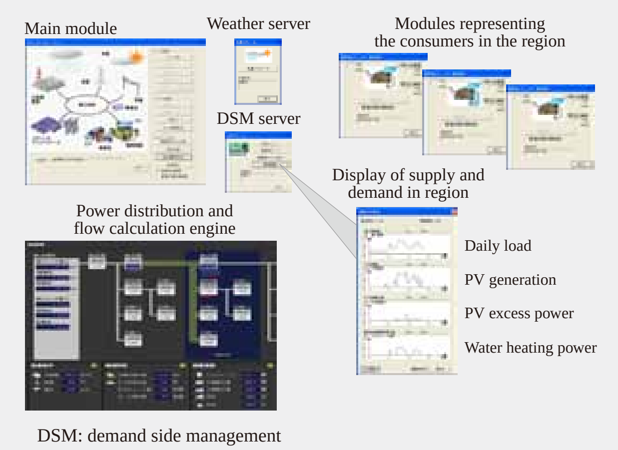

Fig. 11—Module Structure and Key Screens from Prototype System for Control of Local Photovoltaic Power Generation and Consumption.
The prototype was configured by linking various modules together on the plug and play module integration platform of the smart grid simulator.

These modules interact with each other. For example, the power flow module utilizes the demand data modeled by the consumer module to determine the state values across the entire power system while the consumer module uses the grid connection point voltages modeled by the power flow module to calculate how the photovoltaic generation system’s power conditioner (function for preventing over-voltage) will regulate its output (see Fig. 11).

A case study that used this prototype to look at residential consumers found that, compared to individual control of each house, group control of three houses improved absorption of excess power by 1.6 times. Hitachi has also developed a prototype smart charge control system designed to mitigate the effect that wider use of electric vehicles will have on the power system(5), and a prototype demand response control system that uses incentives to encourage consumers to achieve specific consumption targets. These could be configured quickly by using the power flow, consumer, and other modules described above. Hitachi intends to add further models in the future including versions designed for storage batteries.

CONCLUSIONS

This article described the simulation techniques used in the research and development of Hitachi’s main products for the electric power sector, namely steam turbines, gas turbines, generators, and smart grids.

Providing a reliable supply of electric power requires further improvements to the efficiency, reliability, and safety of generation, transmission, and distribution systems. Hitachi intends to continue utilizing the latest simulation technology to respond to these demands.

REFERENCES

(1) S. Senoo et al., “Computations for Unsteady Compressible Flows in a Multi-Stage Steam Turbine with Steam Properties at Low Load Operations,” ASME POWER2010-27096 (July 2010).

(2) Y. Takahashi et al., “Experimental and Numerical Investigations of Endwall Flow in a Bowed Compressor Cascade,” 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 2005-3638 (July 2005).

(3) Y. Horiuchi et al., “Improvement of Heat Transfer Performance of Turbulence Promoter Ribs,” ASME GT2006-91168 (May 2006).

(4) K. Hattori et al., “Performance Assessment Study of a 250 MVA Air-cooled Turbo Generator,” Electric Machines and Drives Conference 2003 IEMDC’03 IEEE International.

(5) T. Ishida, “Feasible Study for the Availability of Electric Vehicles for the Stable Operation in Power System Network,” EVTeC’11, SS-5-20117248 (May 2011).

ABOUT THE AUTHORS

Kiyoshi Segawa

Joined Hitachi, Ltd. in 1990, and now works at the Department of Steam Turbine Research, Hitachi Research Laboratory. He is currently engaged in research and development of new technologies for steam turbine performance upgrades. Mr. Segawa is a member of the Japan Society of Mechanical Engineers (JSME).

Yasuo Takahashi

Joined Hitachi, Ltd. in 2000, and now works at the Department of Gas Turbine Research, Hitachi Research Laboratory. He is currently engaged in research and development of axial compressors for gas turbines. Mr. Takahashi is a member of the Gas Turbine Society of Japan (GTSJ).

Shinichi Higuchi

Joined Hitachi, Ltd. in 1993, and now works at the Department of Gas Turbine Research, Hitachi Research Laboratory. He is currently engaged in the development of gas turbine systems and turbine blades. Mr. Higuchi is a member of the GTSJ and JSME.

Takamitsu Hae

Joined Hitachi, Ltd. in 2001, and now works at the Department of Power Transmission & Distribution Systems Research, Hitachi Research Laboratory. He is currently engaged in research and development of power equipment.

Yasushi Tomita

Joined Hitachi, Ltd. in 1990, and now works at the Department of Smart Systems Research, Information and Control Systems Research Center, Hitachi Research Laboratory. He is currently engaged in research and development of power systems. Mr. Tomita is a member of the Institute of Electrical Engineers of Japan (IEEJ) and The Institute of Electrical and Electronics Engineers, Inc. (IEEE).

Takashi Nishi, Dr. Eng.

Joined Hitachi, Ltd. in 1984, and now works at the R&D Planning Department, New Business Development Division, Power Systems Company. He is currently engaged in planning power systems research and development. Dr. Nishi is a member of the Atomic Energy Society of Japan (AESJ) and Japan Society of Energy and Resources (JSER).