IN JAPAN, THE POPULATION HAS BEGUN TO DECLINE, with an estimated population of 97 million predicted for 2050, namely 31 million lower than in 2010. This estimation suggests that the electric power industry will suffer a severe labor shortage. Conversely, the government of Japan has declared that Japan will achieve carbon neutrality by 2050. This will depend on the electric power industry building future power grids that accelerate the deployment of renewable energy power generation and further streamline how energy is used. These two major factors would compel the electric power industry to introduce advanced energy management and automation systems that will need to be able to cooperate seamlessly with each other, without exception.

This article describes systems to manage energy and automate future power grids as part the effort to achieve carbon neutrality amid labor force shortages. It also focuses on a power grid stabilization system based on a digital twin (PGSS-DT) that could stabilize a future power grid with tremendous renewable energy power generation units and a smaller labor force.

Automated Management and Operations of Future Power Grids
Figure 1 outlines energy management and automation systems for future power grids. Energy management and related systems, including enterprise and markets, are shown on the left and various kinds of automation systems on the right. These systems would work cooperatively via technologies defined by International Electrotechnical Commission (IEC) standards, including IEC 61850 and the Common Information Model (CIM). Through seamless cooperation, these systems will support or automate various tasks when operating, maintaining, and engineering power grids and related work. In the process, they will play a key role within Japanese society, where the birthrate is declining and the population continues to age.

The following subsection describes the energy management and related systems, with automation systems configured to cooperate seamlessly. Please note that cybersecurity...
is outside the scope of this article, as there are too many topics relevant to future power grids to be discussed here, despite the fact that the seamless cooperation mentioned critically depends on this issue.

**Energy Management and Related Systems**
The following systems are categorized into energy management and related tools:
- ✔ systems for a dispatching center
- ✔ analysis tools for operating and planning power systems
- ✔ meter data management system
- ✔ customer support systems
- ✔ asset management systems
- ✔ systems for electric power markets.

Most tend to be owned and operated by grid operators, namely so-called transmission system operators (TSOs) or distribution network operators. This means they exchange data for energy management and related businesses, including asset and customer management, as shown in Figure 2. The interfaces used to exchange information shall be implemented based on the CIM to ensure interoperability. The CIM defines classes as representing various kinds of data used in the businesses of grid operators.

Some systems in this category are linked to an automation system described in the “Automation Systems” subsection. One such example is the role played by the asset management business function, as defined in IEC 61968-1 Ed. 3.0. This business function involves asset record management that registers and maintains various types of asset information. If the information is provided to an engineering process for an automation system online, the labor force for the engineering process could be reduced. To further reduce the labor force, the information will be automatically used...
figure 1. An overview of energy management and automation systems for future power grids. CIM: common information model; DER: distributed energy resource; IEC: International Electrotechnical Commission; MDMS: meter data management system.

figure 2. Business functions for interface reference model in IEC 61968-1 Ed. 3.0.
Seamless cooperation like this could help facilitate control voltage on a feeder and execute fault location, isolation, and service restoration.

and/or processed within the automation system in the future. Achieving this final goal will require closer and more precise cooperation between the CIM and IEC 61850 from the perspectives of data semantic, as well as data usage cases. This final stage of advanced use and process could be called *input once, use anywhere, automatically.*

**Automation Systems**

The following categories apply to automation systems:

- ✔ substation automation systems
- ✔ telecontrol
- ✔ bulk generation systems
- ✔ feeder automation systems
- ✔ systems for wind power generation
- ✔ distributed energy resource (DER), including photovoltaic (PV) generation, controllable loads, and electric vehicles.

These automation systems will be designed and built based on IEC 61850 and related standards, including IEC 61400-25 for wind power generation, IEC 61869-9 for instrument transformers, and IEC 62271-3 for high-voltage switchgears and control gears. These associated international standards help ensure interoperability in various domains. IEC 61869-9, for example, defines stricter specifications for sampled values (SVs) based on IEC 61850, by adding standard sampling rates and sets of values. If IEC 61850 remains in widespread use across various domains, powerful information models and an engineering scheme shall help ensure seamless cooperation between the automation systems mentioned above.

**Applying IEC Information Models to Achieve Carbon Neutrality With a Reduced Labor Force**

This section describes three distinctive systems that employ the IEC information models to achieve carbon neutrality with a reduced labor force. The first, centering on feeder automation, is already in operation, while the others, currently, are simply concepts and visions about future systems.

**A Feeder Automation System Employing IEC 61850**

IEC 61850 has already become a popular choice in the domain of substation automation systems. Other domains have also started using this family of international standards. One example of domains employing IEC 61850 is a feeder automation system in Japan.

Distribution feeders in Japan typically comprise medium voltage (MV, 6.6 kV) lines, MV/low-voltage power transformers, sectionalizers, and several other types of equipment, including step voltage regulators (SVRs). A sectionalizer is a type of switchgear used to change the network topology of distribution feeders and isolate faulty sections from the system. Some sectionalizers contain instrument transformers to measure the current and voltage of the MV feeders. A field controller is installed beside a sectionalizer or other piece of equipment to allow a master unit that is located in a control office to remotely monitor and control them.

The feeder automation system based on IEC 61850 employs an abstract communication service interface and manufacturing message specification in the telecommunication networks. This takes place between a master unit and a field controller and logical node (LN) in a field controller, as illustrated in Figure 3. Initially installed in 2018, the system has been operational ever since, with other systems subsequently installed.

This IEC 61850 application allows seamless cooperation with a substation automation system in the substation from which the feeder originates and a DERs management system that monitors and controls DERs connected to the feeder. Seamless cooperation like this could help facilitate control voltage on a feeder and execute fault location, isolation, and service restoration in the future. It could also eliminate some manual tasks that are currently needed for operation planning and coordination across several sectors, and also reduce the number of maintenance staff dispatched to the field in the event of a fault. These systems could help when introducing DERs with reduced labor forces.

**A Platform for DER Flexibility**

The flexibility provided by DER is expected to help resolve operational power system issues, including congestion and voltage control. Leveraging this flexibility requires a platform on which grid operators, aggregators, and other stakeholders are able to exchange data. The information models specified in international standards help make the platform more connective and expandable. Table 1 describes the platform functions and corresponding information models with the number of international standards. The information models specified by the IEC are expected to facilitate the implementation of a platform for DER flexibility.
This mapping between functions and information models helps clarify technical issues when applying the information models to the DER flexibility platform; this includes the identification of information models for resource registration with construction, resource grouping, and an information creator.

**A PGSS-DT in Real-Time**

This section proposes a PGSS-DT in real time, as a symbolic advanced automation system, going forward. It describes PGSS-DT from the perspectives of background and purpose, conceptual configuration, and the application of all-photonics network technologies, in the context of reduced labor forces.

**Background and Purpose**

A transformation of power grids depends on the types and connection points of generators, as well as changing the monitoring, control, operation, and restoration requirements. Figure 4 outlines the transformation for future power grids.

In terms of generator connection points, a tremendous number of inverter-based generators are expected to connect to subtransmission grids, with a voltage ranging from 66 kV to 187 kV, in the case of Japan. Fine resolution, in terms of location and interval, will be required for measurement and status acquisition, to stabilize future power grids. Further, data gathered from the grids shall be imported in real time to one or more applications. Such applications will utilize the concept of a digital twin to analyze grid stability and/or execute preventive control. All processes will need to be executed in real time, as grid situations are variable and volatile. A PGSS-DT is proposed as a promising concept and some component technologies are already being studied.

**A Conceptual Configuration**

Figure 5 illustrates a conceptual configuration of PGSS-DT, which has almost the same design and functionality as a synchrophasor system. Both systems include devices in substations and are physically configured with one or more data concentrators. They also collect data that is measured or monitored simultaneously in multiple substations and in real time. Conversely, the PGSS-DT must have functionalities that a synchrophasor system lacks. Namely:

- Real-time model updates, to analyze the dynamic characteristics of a power grid
- A cybersecurity mechanism that does not prevent the PGSS-DT operating, regardless of circumstances.

The next generation of intelligent electronic devices (IEDs) used for PGSS-DT will include advanced connectivity to reduce the engineering workload, as well as ultrahigh speed data transmission via IEC 61850. With advanced connectivity in mind, the information stored in the engineering files will be set up automatically and remotely. This information includes LN instances that hold predefined values of objects to be monitored or controlled (e.g., names and ratings), which are then applied to the IED. This information is configurable by referencing the data managed in energy.
management and related systems. Accordingly, advanced connectivity will be realized when the PGSS-DT and external systems are able to work together.

The server for the digital twin updates one or more power grid models in real time, according to the data from IEDs via the data concentrator and dispatcher. Updating these models in real time is key to realizing the digital twin. The updated model is then used to analyze power grid stability and make a switching plan as a form of preventive control to further stabilize the power grids. It is also used to tune up settings so

<table>
<thead>
<tr>
<th>Group</th>
<th>Function</th>
<th>Description</th>
<th>Information Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Registration and information</td>
<td>Registration of aggregators</td>
<td>To register a new aggregator entry and acquire its data for approval.</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td>management</td>
<td>Registration of DER</td>
<td>To register a DER entry and assign an identifier to it</td>
<td>✔ CIM (IEC 61970-301, IEC 61968-11)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>✔ SCL (IEC 61850-6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>✔ LN (IEC 61850-7-420)</td>
</tr>
<tr>
<td>Management of DER group</td>
<td>Management of DER group</td>
<td>To manage DERs operated by each aggregator</td>
<td>✔ CIM (IEC 61968-5)</td>
</tr>
<tr>
<td></td>
<td>Association management</td>
<td>To associate a DER with a point of power system topology</td>
<td>✔ CIM (IEC 61970-301)</td>
</tr>
<tr>
<td></td>
<td>Management of market service</td>
<td>To define a new market service and manage its terms and conditions</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td>Market and contracts</td>
<td>Request registration</td>
<td>To specify a request for DER flexibility</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td></td>
<td>Request release</td>
<td>To release a request for DER flexibility to registered aggregators</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td></td>
<td>Validation</td>
<td>To validate an offer submitted by an aggregator</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td></td>
<td>Optimization</td>
<td>To determine which offers meet the released request and assign the aggregators to the released request</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td></td>
<td>Notification of optimization</td>
<td>To notify the optimization results to all aggregators having submitted offers</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td></td>
<td>results</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Contract approval</td>
<td>To approve the contracts with the aggregators</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td></td>
<td>Contract management</td>
<td>To manage the contents of contracts, including contractors, DERs and services</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td>Operations</td>
<td>Dispatch optimization</td>
<td>To generate optimized dispatches in considerations of the contracts</td>
<td>✔ CIM (IEC 61970-301)</td>
</tr>
<tr>
<td></td>
<td>Dispatch delivery</td>
<td>To deliver optimized dispatches to the DERs operated by the aggregators</td>
<td>✔ LN (IEC 61850-7-4/-7-420)</td>
</tr>
<tr>
<td></td>
<td>Fail safe</td>
<td>To control DERs to avoid a serious accident in cases where telecommunications and/or power system malfunction</td>
<td>✔ LN (IEC 61850-7-4/-7-420)</td>
</tr>
<tr>
<td></td>
<td>Event notification</td>
<td>To notify an event on the power system to stakeholders</td>
<td>✔ CIM (IEC 62325-301, IEC 62746-4)</td>
</tr>
<tr>
<td>Settlement</td>
<td>Data acquisition for settlement</td>
<td>To acquire data about the results of DER responses to calculate the settlement amount.</td>
<td>✔ COSEM (IEC 62056-6-2)</td>
</tr>
<tr>
<td></td>
<td>Calculation</td>
<td>To calculate the settlement amount</td>
<td>✔ IEC 61968-11/-9</td>
</tr>
<tr>
<td></td>
<td>Approval</td>
<td>To approve</td>
<td>✔ IEC 61968-11</td>
</tr>
</tbody>
</table>

Please note that IEC 62746-4 is under development. COSEM: companion specification for energy metering; SCL: system configuration description language.
figure 4. Power system transformation going forward.

figure 5. A conceptual configuration of the power grid stabilization system based on a digital twin. BESS: battery energy storage system; IED: intelligent electronic device; ShR: shunt reactor; SC: shunt capacitor; WT: wind turbine.
The next generation of intelligent electronic devices used for PGSS-DT will include advanced connectivity to reduce the engineering workload, as well as ultrahigh speed data transmission via IEC 61850.

that protective relays can adapt to power grid requirements. The switching planning and tuning up of parameters for protective relays may require exchanges of data to/from the energy management and related systems via the interfaces, based on the CIM. Dispatching commands and setting values are transmitted to the IEDs, according to IEC 61850 via the data concentrator and dispatcher.

All PGSS-DT devices are equipped with a cybersecurity mechanism that ensures the security of data transmission and engineering. This mechanism, particularly when applied to data transmission, should not interfere with the operation of the PGSS-DT. This is the case even when some or all of its element malfunction, although such events can result in decreased cybersecurity measures. Consequently, it is necessary to incorporate some form of fail-safe mechanism and/or physical configuration to fulfill these requirements.

The Central Research Institute of Electric Power Industry is presently researching a type of PGSS-DT, dubbed real-time smart digital twin and is developing elemental technologies pertaining to data transmission, real-time model updating, and a cybersecurity mechanism with fail-safe features.

Information Models and Messages in PGSS-DT

The PGSS-DT is expected to be implemented with various types of IEDs provided by multiple manufacturers because the IEDs for PGSS-DT will be installed in almost all substations in a single TSO. Moreover, the IED for PGSS-DT will be connected to existing merging units for substation automation systems (SASs). The IEDs will employ LNs and messages specified in IEC 61850 to ensure interoperability among the merging unit, IED for PGSS-DT, and data concentrator and dispatcher. Figure 6 illustrates an example deployment of LNs and messages in PGSS-DT. The merging unit sends sampled current and voltage values to the IEDs for both PGSS-DT and SAS using the SV message. The IED for PGSS-DT calculates the root mean-square (RMS) values of current and voltage based on these SVs and then transmits these values to the data concentrator and dispatcher using routable SV (R-SV). This RMS value calculation is performed by the measurement LN (MMXU) that resides in the IED for PGSS-DT.

In instances where changes to the power grid topology are necessary for maintaining stability, the automatic switching sequence LN sends operation commands to the PGSS-DT IEDs that control specific switchgears. These PGSS-DT IEDs, upon receiving the commands, control the switchgears using generic object oriented system event (GOOSE) messages that are transmitted to the merging units.

This level of interoperability, founded on the LNs and messages delineated in IEC 61850, is expected to not only reduce the workforce needed for power grid analysis but also help stabilize power grids with a substantial amount of installed renewable energy resources, specifically those with inverter-based generators.

Application of All-Photonics Network Technologies to PGSS-DT

The all-photonics network (APN) is a communication network that directly connects endpoints with optical paths. APN technologies look well-placed to implement the PGSS-DT because they can provide the following advanced capabilities:

- ultrawide bandwidth
- ultralow and deterministic latency
- ultrahigh reliability
- scalability.

Figure 7 outlines APN from configuration and signal transmission perspectives. An APN comprises optical fibers and all-photonics node devices. In the APN, a wavelength division-multiplexing technique is used to prepare

---

**Figure 6.** An example of LN deployment and messages in PGSS-DT. ASWI: automatic switching sequence LN; R-SV: routable SV; TCTR: current transformer LN; TVTR: voltage transformer LN.
The APN research project aims to deliver ultralow end-to-end latency communications, potentially 200 times quicker than existing networks, which require conversions between electric and optical signals for routing. This goal implies that the latency between the IED and the data concentrator and dispatcher could be reduced to mere milliseconds. Moreover, in the APN, latency is expected to be deterministic for each path since the nodes do not employ any queuing scheme.

Through these advantages, the APN could be a platform for the PGSS-DT to transmit data at short intervals from numerous substations; moreover, applying the APN to the PGSS-DT could eliminate the need to use a time synchronization function. In other words, the data concentrator could use all of the paths provided by the APN contingent on numerous paths, meeting the latency requirements for the application. In the example illustrated in Figure 7, the next-generation IED (located in the middle) sends the same data to the data concentrator via four paths. The more paths an application can use, the more reliable its telecommunication. Current applications, including the pulse coded module-based protection relay for transmission line and telecontrol, typically use two paths for the same data transmission; this paves the way for an APN to make telecommunication more reliable.

APN technologies would come from the activities of the innovative optical and wireless network Global Forum, an organization developing all photonics technologies.

According to the combinations of the technologies, including information models and the APN, PGSS-DT could determine and stabilize a power grid to which numerous renewable energy resources are automatically and precisely connected. These characteristics of PGSS-DT could help reduce the amount of labor required by eliminating offline tasks, such as simulations and preventing faults.

**Conclusion**

This article describes systems for future power grids to achieve carbon neutrality with a reduced labor force from the perspective of seamless cooperation. The systems in question must be dramatically refined on an ongoing basis for future power grids to accept more renewable energy resources. CIM and IEC 61850, specified by IEC TC 57, shall facilitate this process that will help relieve labor shortages in Japan.

**For Further Reading**


**Biography**

*Tetsuo Otani* is with the Central Research Institute of Electric Power Industry, Yokosuka-shi 240-0196, Japan.