THE KOREAN ELECTRIC POWER Corporation (KEPCO) has created a number of initiatives for encouraging both green and smart energy in the global energy industry. With the aim of being a smart energy creator, KEPCO conducted R&D for green and smart substations over the last 10 years, which will be implemented in future substations.

The smart (or digital) substation is equipped with protection and automation schemes in an IEC 61850 environment that provides a platform for smart feeder (or smart grid) applications. Since the IEC 61850 standard was published, the role of the substation has undergone a paradigm shift. The major role of a conventional substation is to offer voltage-level transformation, key parameter measurements, and line and equipment protection. An advanced substation offers conventional services and also provides progressive functions, such as feeder automation, remote maintenance, and the integration of intelligent electronic devices (IEDs). The future smart substation will not only include additional functionalities but will also provide self-healing protection schemes and grid services for improving power stability and quality.

# Smart and Green Substations

**By Heejin Kim, Jae-Kyeong Kim, Jiyoung Song, Jaegul Lee, Kisun Han, Jeonghoon Shin, Taekyun Kim, and Kyeon Hur**

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# Shaping the Electric Power Grid of Korea

The green substation provides a platform to support the increase of renewable energy (RE) as well as demonstrate the achievement of environment-friendly substations by reducing the production of air pollutants, such as sulfur hexafluoride (SF6) gas. For example, since 2016, the 23-kV gas-insulated switchgears (GISs) with SF6, used for more than 20 years in the Korean electric power grid, are being replaced by GISs with dry air and solid-insulated switchgears (SISs). A modular green substation is proposed for interconnecting the increasing amounts of RE. This example of the future green substation will play an important role in integrating remotely located RE sources (RESs) into the power grid.

The expanded adoption of distributed energy resources (DERs) changes the grid dynamics by displacing the large fossil fuel and synchronous generators, thereby weakening the grid strength, requiring new capabilities and functionalities for the future substations. The fundamental changes and opportunities of the future power system with improved reliability, availability, efficiency, and security can be summarized as follows:

- ✔ the high penetration of DERs
- ✔ the high integration of controllable devices for power system support
- ✔ the interconnection of power systems in different countries and regions via a dc grid (or supergrid)
- ✔ the convergence of IT, automation, and power engineering
- ✔ the advanced control and protection schemes
- ✔ the communication networks in power systems.

With these priorities in mind, various projects, such as communication network development for digital substations, modular green substations for increasing the hosting capacity of RESs, online load modeling for reliable power system operation, phasor-measurement unit (PMU) data acquisition and analysis systems, and the Jeju Island testbed for the smart grid, have been undertaken in the Republic of Korea. The following sections will introduce these efforts for future smart and green substations to shape the electric power grid of the Republic of Korea.

## Overview of the Korean Electric Power System

### *Brief History of Its Electric Power Industry*

In 1887, the first light bulb was illuminated at the royal palace in Seoul. Over the last 130 years, Korea's electric power industry has grown dramatically. KEPCO was established with the Electricity Enterprises Act (three electric companies were merged and became a wholly government-owned corporation) in 1961. KEPCO is the only electric utility company that owns the transmission and distribution system in the Republic of Korea. The overall power demand in the country has grown significantly since the 1970s due to industrialization and rapid economic growth. The maximum demand was 5.4 GW in 1980 and 41 GW in 2000, and the highest demand was 92.5 GW in 2018. The peak demand has increased by more than 17 times over the past 38 years.

The first high-voltage (HV) dc interconnection between Jeju Island and the main peninsula was completed in 1998. The purpose of the HVdc installation was to improve the reliability of the power system of Jeju, the biggest island in the Republic of Korea, and to reduce the cost of its electricity.

### *Korea Electric Power Substation Statistics*

The Republic of Korea is currently one of the largest consumers of electrical energy in the world, due to the country's rapid economic growth of heavy and chemical industries. The Republic of Korea consumed a total of 507.7 TWh of net electricity in 2017, with 276.6 TWh for industrial purposes, 164.5 TWh for commercial applications, and 66.5 TWh for residential use. The maximum demand reached 92.5 GW in 2018 and is forecast to grow and reach 110 GW in 2030, according to the eighth long-term electricity supply and demand plan published by the Ministry of Trade, Industry, and Energy. The total installed generation capacity in the Korean power system is currently 119 GW.

Table 1 shows the transmission, substation, and distribution facilities in the Republic of Korea from 1992 through 2017. As is shown, the number of 345- and 154-kV transmission and substation facilities has increased, but the number of 66-kV transmission facilities has decreased. Since 1990, these facilities have been intentionally retired to improve transmission efficiency.

KEPCO has established a new voltage level (70 kV) to accommodate increasing amounts of RESs in accordance with its long-term electricity supply and demand plan. The first 70-kV substation will be installed in 2022 and reflect a modular design. While it typically takes four years to install a conventional substation, strategically locating modular substations would likely expedite the process significantly.

## Outlook for Korea's Efforts in Smart Substation Development

### *Development of Digital Substations and Communication Network*

After the publication of IEC 61850 in 2004, a task force to promote digital substations was created. Table 2 is an overall road map for the implementation of the smart substation. After several pilot projects, the first 154-kV digital substation was installed in 2013. A total of 32 digital substations were installed in 2018, and 740 more are expected to be installed by 2034, which includes the digitalization of existing substations. Figure 1 shows the status and future installation plans for digital substations in the Republic of Korea. As the number of digital substations increases annually, the proportion of total digital substations is expected to reach 83% in 2034.

Smart substation features developed during the preparation stage for the application of IEC 61850 to establish communication networks for digital substations included the following: substation virtual servers, substation gateways, IED explorer (software that performs IEC 61850 client simulator for the testing of IEC 61850-based IEDs), a digital

**table 1. Transmission, substation, and distribution facilities in the Republic of Korea.**

| Division | | 1992 | 1997 | 2002 | 2007 | 2012 | 2017 |
|---|---|---|---|---|---|---|---|
| Transmission facilities (C-km) | 765 kV | — | — | 662 | 755 | 835 | 1,019 |
| | 345 kV | 5,259 | 6,442 | 7,496 | 8,284 | 8,770 | 9,746 |
| | 154 kV | 11,631 | 15,097 | 18,144 | 19,917 | 21,578 | 22,831 |
| | 66 kV | 3,579 | 2,513 | 1,402 | 338 | 208 | 128 |
| | Total | 20,469 | 24,052 | 27,704 | 29,294 | 31,391 | 33,724 |
| Substation facilities (MVA) | 765 kV | — | — | 7,110 | 23,114 | 29,116 | 38,116 |
| | 345 kV | 26,339 | 46,009 | 69,078 | 95,279 | 115,598 | 131,880 |
| | 154 kV | 32,982 | 58,706 | 83,364 | 109,268 | 126,143 | 141,538 |
| | 66 kV | 2,103 | 1,813 | 1,073 | 454 | 312 | 240 |
| | 22 kV | 508 | 308 | 213 | 134 | 78 | 94 |
| | Total | 61,932 | 61,932 | 160,838 | 228,249 | 271,247 | 311,868 |
| Number of substations | 765 kV | — | — | 3 | 5 | 5 | 7 |
| | 345 kV | 20 | 36 | 69 | 81 | 68 | 112 |
| | 154 kV | 223 | 335 | 472 | 571 | 636 | 713 |
| | 66 kV | 74 | 48 | 20 | 6 | 3 | 3 |
| | 22 kV | 14 | 8 | 10 | 6 | 3 | 4 |
| | Total | 331 | 427 | 574 | 669 | 715 | 839 |
| Distribution facilities | Line (C-km) | 255,340 | 326,506 | 366,983 | 401,485 | 442,641 | 481,365 |
| | Transformer (MVA) | 24,072 | 39,596 | 71,977 | 92,963 | 104,081 | 114,236 |

C-km: Circuit kilometer.

substation engineering tool called *S-CLICK* (it sets up and verifies communication and data exchange between various IEDs and operating systems of a digital substation), substation human–machine interface (HMI), IEC 61850 server/client conformance testing device, and application software programs for the substation automation system. Several other items needed to be developed, including protection and control IEDs [e.g., protective relaying devices, on-load tap-changer controllers, circuit breaker (CB) controllers, capacitor bank switches, recloser controllers, voltage regulators, and shunt reactor switches], power quality IEDs, a bay controller (controlling a bay in a substation), a merging unit (a device that enables the implementation of IEC 61850 by converting the analog signals from the conventional current transformers and voltage transformers into IEC 61850 sampled values), and a generic object-oriented substation event (GOOSE) messaging agent (software that monitors and publishes GOOSE messages to test and verify GOOSE messages of IEDs).

**table 2. A road map of the smart substation (from 2008).**

| Development Stage | Duration | Objective |
|---|---|---|
| Preliminary | 2008–2009 | ✔ Education and training |
| Preparation | 2009–2012 | ✔ Pilot project for digital substation<br>✔ Various types of IED development<br>✔ Merging unit development<br>✔ Engineering tool (S-CLICK) development for digital substation<br>✔ GOOSE agent software development<br>✔ Development of IEC 61850 server/client conformance testing device<br>✔ Field test |
| Implementation | 2013–2017 | ✔ Digital substation installation and operation<br>✔ Digital substation smart operation system development<br>✔ Error collection and performance improvement |
| Innovation | 2017–2019 | ✔ Upgrade for IEC 61850 edition 2.0<br>✔ Development of AI-based automatic substation restoration system |
| Diffusion | 2019–2030 | ✔ Demonstration project for AI-based automatic substation restoration system<br>✔ Design and implementation of intelligent digital substation based on IEC 61850 process bus<br>✔ Expansion of substation automation system + substation asset management system + substation equipment monitoring and diagnostics system + AI-based automatic substation restoration system<br>✔ AI-based autonomous operation unmanned substation |

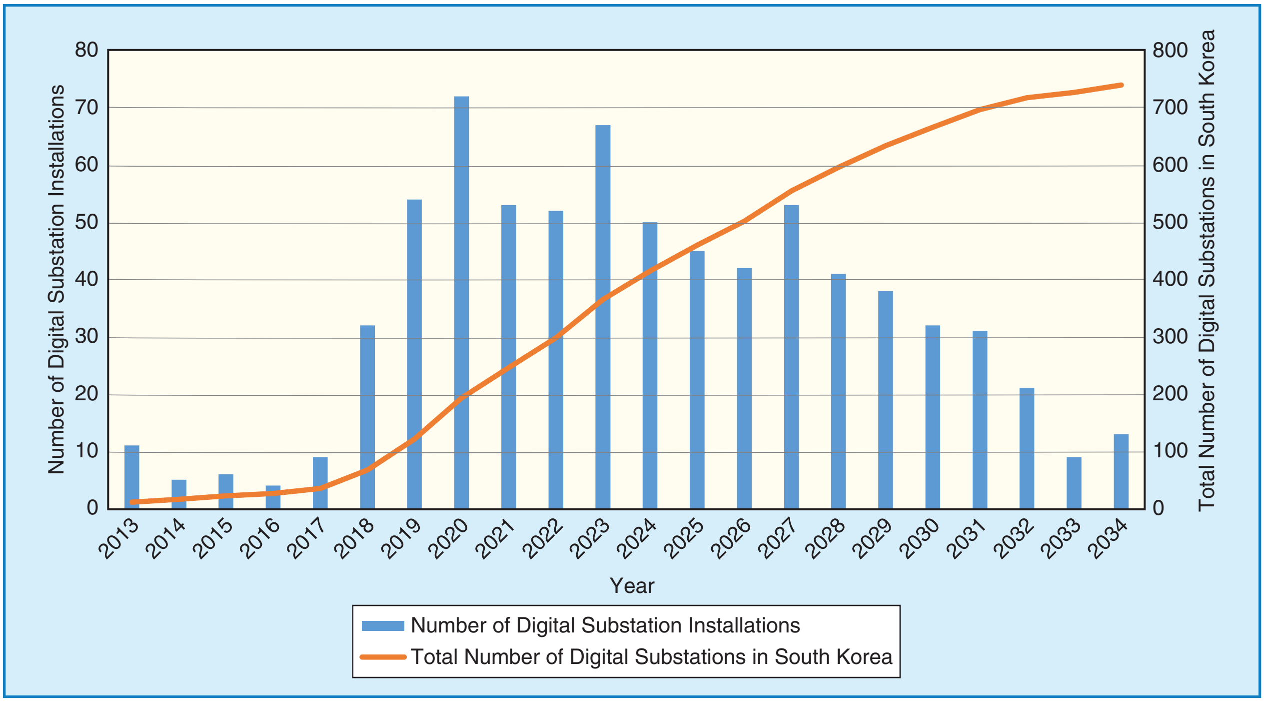



**figure 1.** The status and future plans for digital substation installations in South Korea.

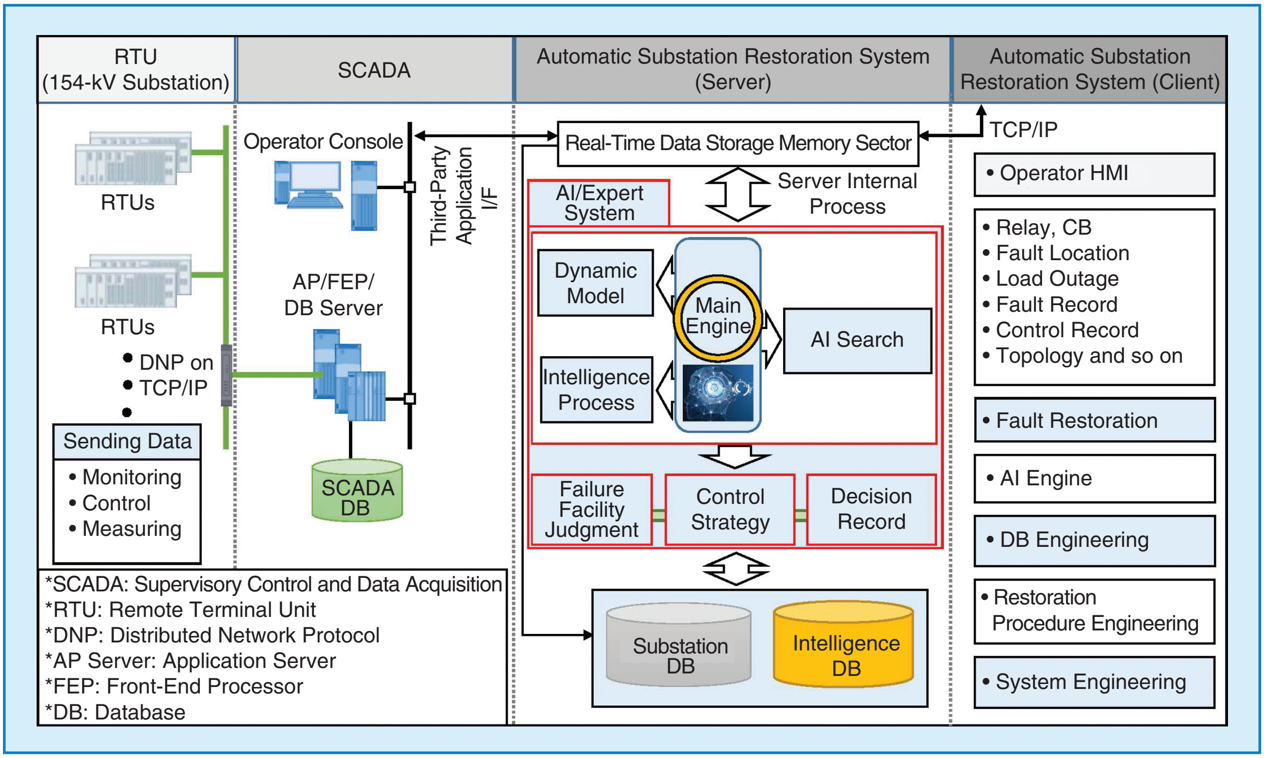



**figure 2.** The proposed architecture of the automatic substation restoration system.

IEC 61850 expects interoperability of various devices in a substation, but it has been observed that complete interoperability cannot be guaranteed when devices from various vendors are installed. To solve this, the development of the second version of a client conformance testing system based on IEC 61850 was started during the innovation stage, as seen in Table 2. Procedures and systems for the test and verification of the digital substation's high-level system are expected to be developed. This will support installation by verifying the interoperability of IEDs in digital substations, which are being installed more often in the future Korean power grid.

### *Development of an Automatic Substation Restoration System*

When a substation is tripped due to a fault, it needs to be restored as soon as possible. Fault isolation and substation restoration improve the reliability of a power system. As the complexity of the modern grid increases, a new machine-learning-based automatic substation restoration strategy will replace the existing expert system-based algorithms and reinforce system restoration. Once a fault occurs, the faulty zone will be instantly identified, and a smart strategy for restoring the system will be executed, which will complete restoration in 1 min. By comparison, the average recovery time, over the past 10 years, of the existing fault recovery system has been 4.8 min. The automatic restoration system should help avoid potential failures due to human errors in the existing system. Figure 2 shows the architecture of the automatic substation restoration system using artificial intelligence (AI). This project will be completed in 2019, and an automatic substation restoration system demonstration project in substations will be implemented from 2019 to 2020. Depending on the results of the project, the automatic substation restoration system may be expanded to other substations.

### *Advanced Metering Infrastructures*

KEPCO has expanded metering infrastructure in substations to provide situational awareness of the grid state and measurements of data. These details inform power system operations and enable the accurate analysis of the system impacts due to the expanded adoption of DERs. Currently, KEPCO uses PMUs in several HV substations (e.g., 765 and 345 kV) to monitor system status. In substations (e.g., 345 and 154 kV) without PMUs, a power quality meter is used for system monitoring as well as data measurements. In 22.9-kV substations, a power quality management system (PQMS) monitors the state of the system as well as power quality. The data from these advanced metering infrastructures (AMIs), analytical models of generators, transmission lines, and loads have been developed that improve the accuracy of power system analysis.

### *Online Load Modeling*

Because power system data from substations can validate dynamic load models for power system stability analysis, a load-modeling automation system (LMAS) was developed. Figure 3 illustrates the overall data and information flow

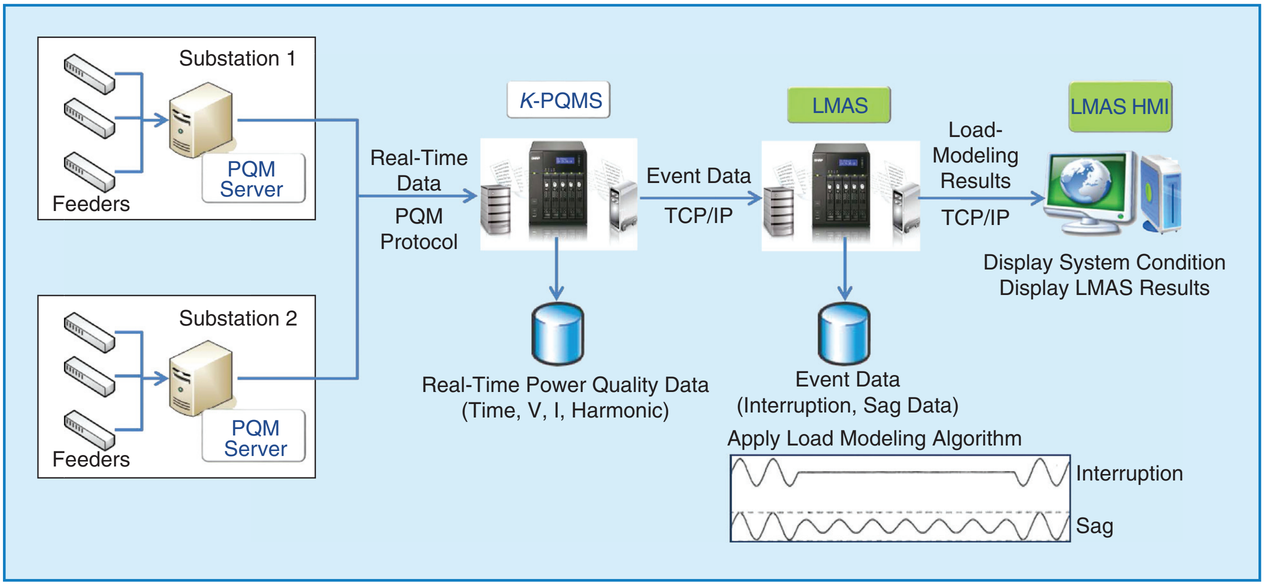



**figure 3.** The data flow of the LMAS of KEPCO. PQM: power quality meter.

of the LMAS. Whenever an event (e.g., a transmission line fault) occurs in the power system, the metering infrastructure of each substation measures it so it is transferred to the central KEPCO PQMS (K-PQMS). The K-PQMS builds a database that includes time, voltage, current, frequency, harmonics, and flicker data and then selects suitable data for load modeling based on the predefined decision criteria. The selected data are transferred to the LMAS server, and the load models for the corresponding buses are developed. This entire process is completed automatically, and the results are displayed on the LMAS HMI.

With the expansion of smart substations as well as AMIs to provide quality data on system states, more accurate and high-quality grid data will be obtained. Thus, a plan was established to build a comprehensive online load-modeling infrastructure based on an LMAS, to include the following:

- ✔ event-driven online load modeling based on state estimation data from the energy management system and data from substations
- ✔ load-model database construction and analysis for developing the representative model by season and time
- ✔ a real-time validation of the representative models through continuous monitoring at the smart substation
- ✔ the continuous validation and updating of the representative load models through big data analysis and defining the representative model by season and time.

The aforementioned online load modeling should improve the reliability of the results from the power system analysis.

## Increment of DERs and the Emergence of a Modular Green Substation

The Korean government aims to increase the proportion of RESs to more than 20% of total generation by 2030. This would require approximately 60 GW of RE facilities (Table 3). To meet this goal, a government policy that promises interconnection of RESs under 1 MW has been announced, the Guarantees Interconnection of Renewables policy. A large capacity of renewables is expected to be connected in the Korean power grid shortly. Remotely located DERs on long distribution lines, however, could cause power quality issues and adversely affect the voltage stability of the distribution network. Location and size uncertainties in future renewable installations also make it difficult to screen and confirm suitable locations for interconnections and perform timely grid reinforcement studies. In addition, the high penetration of DERs could threaten the frequency and voltage stability of the entire power system. Installing modular substations is one option to address these issues and increase DER hosting capacity.

### *Modular Green Substation (G-Platform)*

Modular or mobile substations are not new, but they have not yet been installed in the Republic of Korea. These substations

**table 3. Propects for RE growth in the Republic of Korea (eighth electrical power supply and demand plan, December 2017).**

| | 2017 | 2022 | 2026 | 2030 |
|---|---|---|---|---|
| Generation capacity (GW) | 11.3 (9.7%) | 23.3 (16.4%) | 38.8 (25.4%) | 58.5 (33.7%) |
| Generation amount (TWh) | 34.4 (6.2%) | 58.3 (9.6%) | 89.5 (14.4%) | 125.8 (20%) |

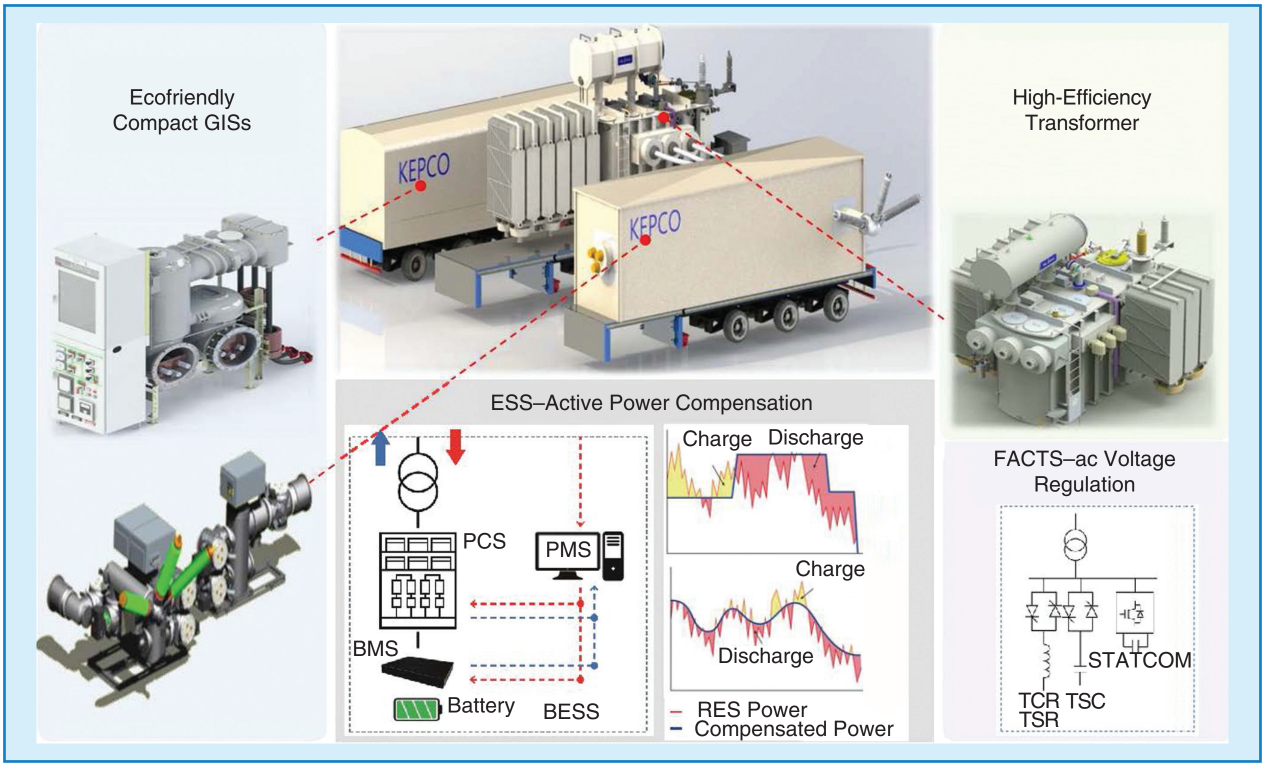



**figure 4.** The configuration of the G-platform. PCS: power conditioning system; BESS: battery ESS; BMS: battery management system; PMS: power management system; TCR: thyristor-controlled reactor; TSR: thyristor-switched reactor; TSC: thyristor-switched capacitor; STATCOM: static synchronous compensator.

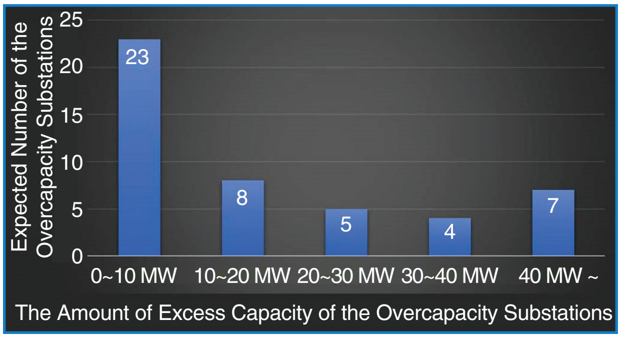



**figure 5.** The preliminary study results for the future renewable generation installation (August 2016). The excess capacity of 76.5% of overcapacity substations is lower than 30 MW.

have been manufactured by several companies across the globe. MarketsandMarkets, a company that provides market analysis reports of segmentation, trends, share, and forecasts, forecasted the growth of the modular substation market from US$10.782 billion in 2015 to US$16.477 billion in 2020. While there was no historical need and market for modular substations in the Republic of Korea, the government has adopted this technology to achieve its RE vision. Such substations are planned to interconnect RESs, which are called *modular green platforms* (*G-platforms*).

The design of G-platforms will be optimized to integrate RESs and be environmentally friendly. The G-platform will increase the capacity of the substation and also minimize the adverse effects of intermittent RE and volatility through communication between the G-platform and the RESs. Figure 4 illustrates the concept of the G-platform, which is in a container and can be configured with a 170-kV GIS, a 23-kV GIS, a 154-kV/22.9-kV transformer, and connections for an energy storage system (ESS) and a flexible ac transmission system (FACTS). ESSs and FACTSs can be installed as needed to improve the power quality and stability of the grid with a high penetration of DERs.

## Capacity Determination of the G-Platform

Figure 5 shows results of a preliminary study conducted in August 2016 for renewable generation installations that were planned for 2018. Results showed 47 of the 698 substations with 154-kV/22.9-kV transformers were going to be over capacity in 2018 due to RES connections. The study results also showed that 97 substations would exceed 50% of their capacity, of which 63 substations would exceed 70%. The number of overcapacity substations would gradually increase with the addition of RESs, as was anticipated in the near future. Given the difficulties of increasing the hosting capacity of the RESs, the urgent need for G-platforms became apparent. Figure 5 shows that under 30 MW of excess capacity is available in 76.5% ($[(23+8+5)/47]\times 100\%$) of the substations. Thus, installing G-platforms with a 30-MW capability could provide a sufficient margin to 76.5% of the substations with limited overcapacity. A transformer capacity of 30 MVA in the G-platform was determined as meeting weight, economy, and urgency requirements in the preliminary study.

## Connecting the G-Platform for RE Integration

Figure 6 is an example of a G-platform installation that directly connects an existing substation and remotely located small-scale RE resources to a transmission line. Candidate locations for this application are shown in Figure 7. The advantage of this connection method is reducing the need for rights of way and cost savings resulting from lower line installation

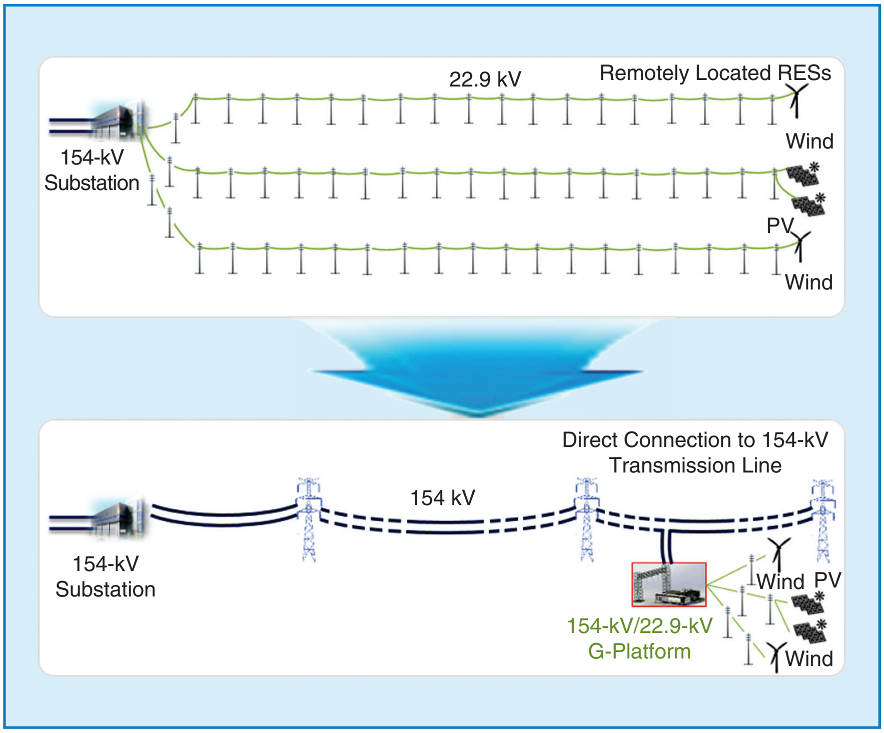
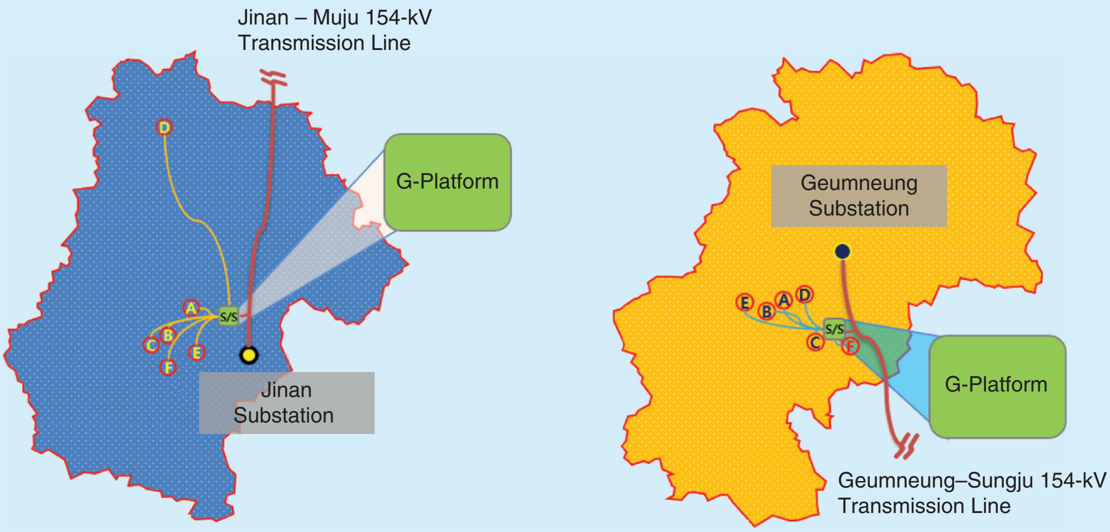



**figure 6.** An example of the G-platform installation. PV: photovoltaic.




| | Types of Renewable | Distance From Substation (km) | Capacity (kW) |
|---|---|---|---|
| A | PV | 4.3 | 6,000 |
| B | PV | 7.5 | 3,000 |
| C | PV | 7.1 | 2,000 |
| D | PV | 23.1 | 2,000 |
| E | PV | 4 | 8,000 |
| F | PV | 6.7 | 2,000 |

| | Types of Renewable | Distance From Substation (km) | Capacity (kW) |
|---|---|---|---|
| A | PV | 6.9 | 100 |
| B | PV | 7.5 | 100 |
| C | PV | 7.1 | 100 |
| D | PV | 6.1 | 100 |
| E | PV | 8.1 | 200 |
| F | PV | 15.2 | 19,500 |

**figure 7.** The candidate locations of the direct connection between a G-platform and a transmission line. PV: photovoltaic.

costs and decreased system losses. This connection would improve the voltage stability in the distribution system. The G-platform can also be interconnected in parallel with existing substations, especially when the existing substation does not have any additional space for expansion.

The advantages of the G-platform are summarized as follows:

- ✔ The installation is fast, simple, and flexible because of the modular design and the capacity upgrade, and installation location change is easy.
- ✔ At strategic locations, it is expected to face minimal public opposition because of its compact design.
- ✔ Because of the ESS, it can act as a virtual power plant and minimize the adverse effects of variations in generation output from renewables. This means that a DER with a G-platform can be used as a dispatchable generator.
- ✔ In the event of a failure of the existing substation, it can be installed quickly to prevent a long outage period.

KEPCO is developing a standard specification for the installation of the G-platform and the technologies for

**table 4. Existing and planned HVdc and FACTS substations in the Republic of Korea (as of March 2019).**

| Type | Year | Capacity | Location | Status |
|---|---|---|---|---|
| HVdc | 1998<br>2019<br>(refurbishment) | 300 MW | Jeju HVdc No. 1 | Under refurbishment |
| UPFC | 2003 | 80 MVA | Kangjin Substation | In operation |
| STATCOM | 2009 | ±100 MVar | Migum Substation | In operation |
| SVC | 2010 | ±200 MVar | Dongseoul Substation | In operation |
| STATCOM | 2010 | ±50 MVar | Sinjeju Substation | In operation |
| STATCOM | 2010 | ±50 MVar | Halla Substation | In operation |
| SVC | 2012 | ±200 MVar | Sinpaju Substation | In operation |
| HVdc | 2014 | 400 MW | Jeju HVdc No. 2 | In operation |
| STATCOM | 2014 | ±100 MVar | Sinsungnam Substation | In operation |
| STATCOM | 2017 | ±400 MVar | Sinyoungju Substation | In operation |
| STATCOM | 2017 | ±400 MVar | Sinchungju Substation | In operation |
| STATCOM | 2018 | ±200 MVar | Sinbupyung Substation | Under installation |
| SVC | 2018 | –225 ~ +675 MVar | Sinjaechun Substation | In operation |
| TCSC | 2019 | 555 MVar × 2 | Sinyoungju Substation | Under installation |
| TCSC | 2019 | 595 MVar × 2 | Sinjaechun Substation | Under installation |
| STATCOM | 2018 | ±300 MVar | Godeok Substation | Under installation |
| STATCOM | 2019 | ±300 MVar | Singapyoung Substation | Under planning |
| STATCOM | 2022 | ±300 MVar | Uijeongbu Substation | Under planning |
| STATCOM | 2021 | ±300 MVar | Sinhanul Substation No. 1 | Under planning |
| STATCOM | 2022 | ±300 MVar | Sinhanul Substation No. 2 | Under planning |
| HVdc | 2019 | 1.5 GW | Bukdangjin–Godeok No. 1 | Under installation |
| HVdc | 2020 | 200 MW | Jeju HVdc No. 3 | Under installation |
| HVdc | 2021 | 1.5 GW | Bukdangjin–Godeok No. 2 | Under installation |
| HVdc | 2021 | 4 GW | Sinhanul–Singapyoung No. 1 | Under planning |
| BTB | 2021 | 200 MW | Yangju Substation | Under planning |
| HVdc | 2022 | 4 GW | Sinhanul–Singapyoung No. 2 | Under planning |
| HVdc | 2023 | 2 GW | West Coast Offshore Wind Connection | Under planning |

TCSC: thyristor-controlled series capacitor; UPFC: unified power flow controller; SVC: static VAR compensator monitoring, diagnosis, and control for the G-platform. The optimal capacity and type of the G-platform has also been investigated to increase the hosting capacity of renewables. The G-platform should play a key role in the future green Korean power grid.

## Toward an SF6 Gas-Free Ecofriendly Substation

KEPCO is continuously striving to install ecofriendly substation equipment and develop advanced testing and operational technologies. As part of this effort, HV vacuum CBs (VCBs) have been developed by Korean CB manufacturers since 2016 and will be deployed in 2021. CB interrupting capabilities will be rated 50 kA, and the rated steady-state current will be 3,150 A. Real-time monitoring of the withstand voltage and the mechanical and electrical characteristics of CBs will be implemented to ensure their reliable condition and to predict breakdowns. By not using SF6 in CBs, the project aims to reduce use of greenhouse gases by an equivalent of 300,000 metric tons of $CO_2$ from 2021 through 2030.

An SF6-free ecofriendly GIS with a fluoronitrile/$CO_2$ mixture and an alternative GIS with dry air have been under development since 2017, including maintenance technologies and CBs. KEPCO established the standard specification for an ecofriendly GIS in 2018; the pilot installation of a 170-kV GIS will begin in 2019 and will be used in new substations by 2021. The goal is to reduce the use of greenhouse gases by an equivalent of 120,000 metric tons of $CO_2$ from 2021 through 2030 by not using SF6 in GISs. The 23-kV GISs, which have been used for more than 20 years in the Korean electric power grid, are being replaced by GISs with dry air and SISs. Adopting the new CB and GIS technologies will also improve reliability performance. When an ecofriendly VCB and GIS are successfully developed, more than 100 HV VCBs and GISs per year will be installed in the Korean power grid, either as new or replacement installations.

## Power Electronics-Based Substation

The development of power electronics-based substations (e.g., HVdc and FACTS) has increased significantly during the past few decades. (Table 4 shows existing and planned HVdc and FACTS substations in the Republic of Korea.) Most HVdc ties connect two distinct areas for integrating remote generation, interconnecting grids, and long-distance power transmission. Current HVdc projects in Korea have been chosen as an alternative to the expansion of the 765-kV ac transmission system. Public opposition to 765-kV tower construction has resulted in new HVdc plans for interconnecting the east coast to the west metropolitan load center because of the relatively smaller size of the HVdc transmission facilities and fewer concerns regarding the health effects of HV electromagnetic waves. Because HVdc and FACTS can provide better controllability of power flow, the installation of HVdc and FACTSs will improve the stability and security of the power system.

A voltage-sourced back-to-back (BTB) HVdc is planned at the Yangju substation to control power flows and reduce the short circuit current in the Seoul metropolitan area, which is served by a ring network as shown in Figure 8. Here the level of the short circuit increases as the power system is reinforced

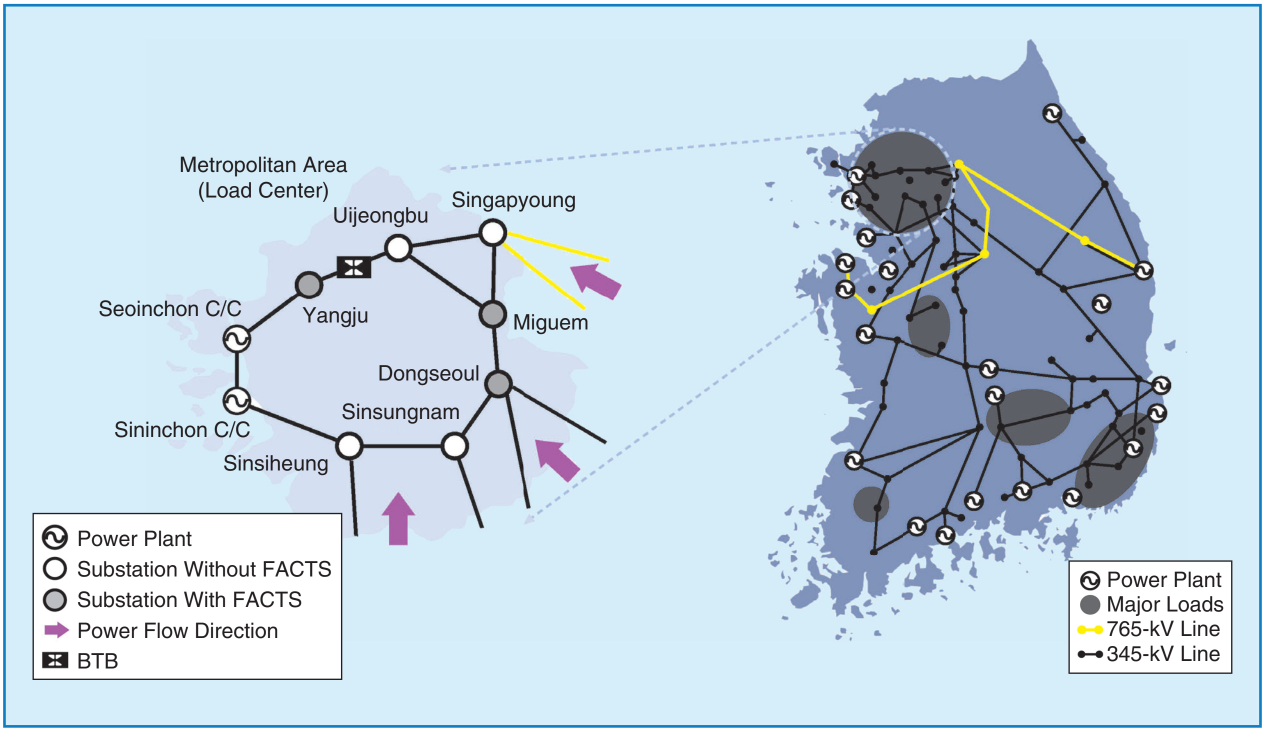



**figure 8.** Substations in the metropolitan area and the location of the BTB HVdc. C/C: combined cycle.

with ac facilities and the interrupt capacity of the CBs in the metropolitan area would need to be increased. The replacement of CBs is challenging due to cost considerations and insufficient installation space at existing substations. In addition, it is difficult to replace several CBs at the same time, which may also interfere with existing system protection coordination. HVdc applications reduce the short circuit capacity and control both the active and reactive power (especially using voltage source converters) that improves the stability and security performance of the entire power system.

Controlling power flow in an ac power system is difficult, but it is easily achievable in a dc system. Power electronics-based substations can be called *smart substations*. HVdc and FACTS equipment, which has high control bandwidth, can provide grid services, such as voltage regulation, black start, special protection schemes (SPSs), virtual inertia support, and primary and secondary frequency regulation. For example, this type of substation might prevent a blackout through coordinated control using SPSs. A sudden power transfer increase achieved through an SPS is a key requirement of the east-metropolitan interconnection HVdc project that reduces the number of required generator trips upon occurrence of a key $N - 1$ contingency (a fault on an existing 765-kV transmission line). The controllability of power electronics-based substations increases the efficiency and reliability of the overall power system and plays a key role in the future power system.

## The Vision for the Future Smart and Green Substations and the Smart Grid

A smart and green power grid may be defined as efficient, reliable, flexible, and resilient with a high integration of DERs; these smart and green substations will be crucial in addressing the challenges presented by future changes to the power system. The functionalities and benefits of smart and green substations are as follows:

- ✔ easier implementation, installation, maintenance, and upgrades, e.g., a modular substation
- ✔ real-time data acquisition and analysis, e.g., online load modeling, behind-the-meter forecasting, and active network management
- ✔ smart control and protection, e.g., fast SPS using HVdc, a modular substation with an ESS, substations with FACTSs, and self-healing (automatic substation restoration system)
- ✔ enhancing the efficiency of the entire power grid, e.g., power flow control of HVdc and optimal grid planning and grid operation
- ✔ an ecofriendly design and construction, e.g., SF6-gas-free substations.

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## Biographies

***Heejin Kim*** is with Yonsei University, Seoul, Republic of Korea.

***Jae-Kyeong Kim*** is with Korea Electrotechnology Research Institute, Uiwang, Gyeonggi-do, Republic of Korea.

***Jiyoung Song*** is with KEPCO Research Institute, Daejeon, Republic of Korea.

***Jaegul Lee*** is with KEPCO Research Institute, Daejeon, Republic of Korea.

***Kisun Han*** is with KEPCO Research Institute, Daejeon, Republic of Korea.

***Jeonghoon Shin*** is with KEPCO Research Institute, Daejeon, Republic of Korea.

***Taekyun Kim*** is with KEPCO Research Institute, Daejeon, Republic of Korea.

***Kyeon Hur*** is with Yonsei University, Seoul, Republic of Korea.