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TECHNICAL SPECIFICATION

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Microgrids –
Part 3-2: Technical requirements – Energy management systems

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FOREWORD

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IEC TS 62898-3-2 has been prepared by subcommittee 8B: Decentralized electrical energy systems, of IEC technical committee TC 8: System aspects of electrical energy supply. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
8B/153/DTS	8B/177/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 62898 series, published under the general title *Microgrids*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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INTRODUCTION

Microgrids can serve various purposes depending on the primary objectives of their applications. They are usually seen as a technical means to manage reliability of supply and to facilitate local optimization of energy supply by controlling distributed energy resources (DER). Microgrids also present a way to provide electricity supply in remote areas, to use renewable energy as a systematic approach for rural electrification and to increase resiliency and security of supply to end users.

IEC TS 62898 series is intended to provide general guidelines and technical requirements for microgrid projects.

IEC TS 62898-1 mainly covers the following issues:

- determination of microgrid purposes and application,
- preliminary study necessary for microgrid planning, including resource analysis, load forecast, DER planning and power system planning,
- principles of microgrid technical requirements that should be specified during planning stage,
- Microgrid evaluation to select an optimal microgrid planning scheme.

IEC TS 62898-2 mainly covers the following issues:

- operation requirements and control targets of microgrids under various operation modes,
- the basic control strategies and methods under various operation modes,
- the requirements of electrical energy storage (EES), relay protection, monitoring and communication under various operation modes,
- power quality.

IEC TS 62898-3-XX subseries technical specifications deal with the technical requirements of microgrids.

IEC TS 62898-3-1 covers the protection and dynamic control of microgrids.

The present document covers microgrid energy management systems (MEMS).

MICROGRIDS –

Part 3-2: Technical requirements – Energy management systems

1 Scope

The purpose of this part of IEC 62898 is to provide technical requirements for the operation of energy management systems of microgrids. This document applies to utility-interconnected or islanded microgrids. This document describes specific recommendations for low-voltage (LV) and medium-voltage (MV) systems.

This document focuses on developing standards of energy management systems aimed for microgrids integrated in decentralized energy systems or public distribution grids. It concerns some particularities that are not totally covered by the existing conventional energy system. The microgrid energy management systems are being studied by various actors (utilities, manufacturers, and energy providers) on actual demonstration projects and application use case. The aims of this document are to make the state of the art of existing energy management systems used in actual microgrids projects, to classify the relevant functions which can be accomplished by microgrid energy management systems, and to recommend necessary technical requirements for energy management systems of future microgrids.

This document includes the following items:

- main performances of key components of microgrid: decentralized energy resources, energy storages and controllable loads),
- description of main functions and topological blocks of microgrid energy management systems (MEMS),
- specification of information exchange protocol between main function blocks, linked to microgrid monitoring and control systems (MMCS).

Main functions of MEMS:

- power and energy management among different resources within microgrid including active and reactive power flows with different time scales,
- power and energy forecasts of microgrid,
- energy balancing between upstream grid and microgrid energy resources according to power and energy forecast and upstream and local constraints,
- economic and environmental optimization,
- possible service capacities such as capacity market auctions and resiliency anticipation: new business models,
- data archiving, trending, reporting and evaluation of operation capacities in various operation modes.

MEMS can have some other additional functions according to microgrid size and actual application cases:

- tariff and market trading management,
- utility ancillary services such as frequency regulation, voltage regulation, power quality and reliability improvement, demand response possibilities, change of operation modes linked to MMCS.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60364-8-82, *Low-voltage electrical installations − Part 8-82: Functional aspects − Prosumer's low-voltage electrical installations*

IEC TS 60364-8-3, *Low-voltage electrical installations – Part 8-3: Functional aspects – Operation of prosumer's electrical installations*

IEC 60870 (all parts), *Telecontrol equipment and systems*

IEC 60870-5-101, *Telecontrol equipment and systems – Part 5-101: Transmission protocols – Companion standard for basic telecontrol tasks*

IEC 60870-5-104, *Telecontrol equipment and systems – Part 5-104: Transmission protocols – Network access for IEC 60870-5-101 using standard transport profiles*

IEC 61850 (all parts), *Communication networks and systems in substations*

IEC 61850-8-1, *Communication networks and systems for power utility automation − Part 8-1: Specific communication service mapping (SCSM) − Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3*

IEC 61850-8-2, *Communication networks and systems for power utility automation − Part 8-2: Specific communication service mapping (SCSM) − Mapping to Extensible Messaging Presence Protocol (XMPP)*

IEC TR 61850-90-1, *Communication networks and systems for power utility automation – Part 90-1: Use of IEC 61850 for the communication between substations*

IEC TR 61850-90-2, *Communication networks and systems for power utility automation – Part 90-2: Using IEC 61850 for communication between substations and control centres*

IEC 61970-1:2005, *Energy management system application program interface (EMS-API) − Part 1: Guidelines and general requirements*

IEC 62351, *Power systems management and associated information exchange – Data and communications security*

IEC 62443 (all parts), *Security for industrial automation and control systems*

IEC 62443-3-3, *Industrial communication networks – Network and system security – Part 3-3: System security requirements and security levels*

IEC 62443-4-2, *Security for industrial automation and control systems – Part 4-2: Technical security requirements for IACS components*

IEC TS 62898-1, *Microgrids – Part 1: Guidelines for microgrid projects planning and specification*

IEC TS 62898-2, *Microgrids – Part 2: Guidelines for operation*

IEC TS 62898-3-1, *Microgrids – Technical requirements – Part 3-1: Protection and dynamic control*

IEC TS 62898-3-4:2023, *Microgrids – Technical requirements – Part 3-4: Microgrid monitoring and control systems*

IEEE Std 1815-2012, *IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol (DNP3)*

MODBUS Application Protocol Specification: https://www.modbus.org/docs/Modbus_Application_Protocol_V1_1b.pdf [viewed 2023-12-12]

3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply. ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 Terms and definitions

3.1.1
energy management system
EMS
system monitoring, operating, controlling, and managing DER and loads

[SOURCE: IEC 60364-8-1:2019, 3.2.1 – modified: "Electrical" has been deleted from the term, "energy resources and loads of the installations" has been replaced by "DER and loads".]

3.1.2
distributed energy resources
DER
generators (with their auxiliaries, protection and connection equipment), including loads having a generating mode (such as electrical energy storage systems), connected to a low-voltage or a medium-voltage network

[SOURCE: IEC 60050-617:2017, 617-04-20]

3.1.3
microgrid energy management system
MEMS
system operating and controlling energy resources and loads of the microgrid

[SOURCE: IEC 60050-617:2018, 617-04-25]

3.1.4
microgrid controller
physical device/system which includes MMCS functions and can include MEMS as well, for example, in small size microgrid

3.1.5
microgrid monitoring and control systems
MMCS
computer or PLC based system performing real time monitoring and control of microgrid

3.1.6
point of common coupling
PCC
point in an electric power system, electrically nearest to a particular load, at which other loads are, or could be, connected

[SOURCE: IEC 60050-614:2016, 614-01-12]

3.1.7
point of connection
POC
reference point on the electric power system where the user's electrical facility is connected

[SOURCE: IEC 60050-617:2009, 617-04-01]

3.1.8
state of charge
SOC
available capacity in a battery pack or system expressed as a percentage of rated capacity

[SOURCE: ISO 12405-4:2018, 3.20]

3.1.9
state of health
SOH
general condition of a battery and its ability to deliver the specified performance compared with a new battery (0 % to 100 %)

3.2 Abbreviated terms

EES electric energy storage

ESS energy storage system

4 General

4.1 System architecture and functional mapping

Generally, microgrids can be integrated into the electric power system (see Figure 1), and MEMS is one of the key components or functions of microgrid. Figure 1 is based on a general view and the displayed blocks have other possibilities depending on the size of the microgrids and the type of applications.

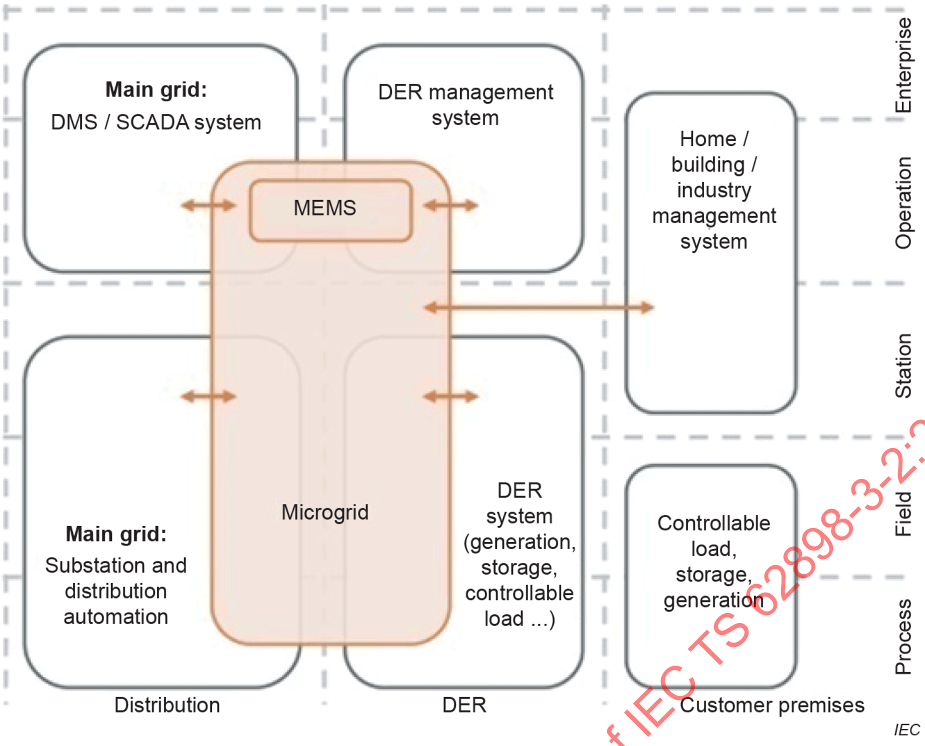


Figure 1 – Conceptual map of a power system consisting of a microgrid

The operation control system of a microgrid can be divided into three layers according to the time scale, namely the energy management layer, the monitoring and control layer, and the protection and dynamic control layer, see Figure 1.

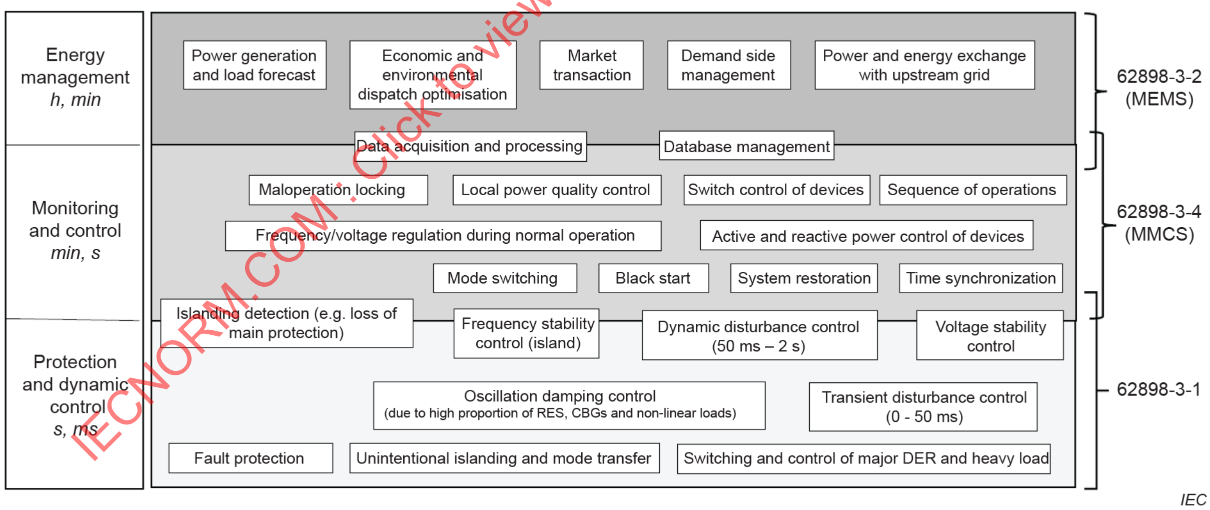


Figure 2 – Functional mapping for operation and control of microgrids

The protection and dynamic control layer of the operation control system of microgrids is not handled by the microgrid energy management module as an independent module since this layer is mainly for real-time control of DER, and its response time is the shortest.

The energy management works mainly in energy management layer and partially in the monitoring and control layer for small size microgrids. In Annex A, MEMS functions are performed or detailed in some actual application cases.

For small microgrids, MEMS and MMCS could be managed by the same microgrid controller (see 4.4.2, Figure 4).

The following two documents are very important for LV prosumer installations and for microgrid as well:

- IEC 60364-8-82, which provides more detailed requirements regarding low voltage prosumer electrical installation.
- IEC TS 60364-8-3, which provides more detailed consideration regarding low voltage prosumer electrical installation.

The protocol conversion in MEMS should be based on the same principle as described in IEC 61970-1:2005; see also Annex B of the present document.

4.2 Stand-alone MEMS

Microgrid energy management as a stand-alone system is intended to handle only the operation and control system of microgrids. It is configured to have the functions with long time scales, such as power generation forecasting, economic dispatching, and demand side management.

4.3 Integrated MEMS

Microgrid energy management module as a system integrated into a microgrid controller is intended to handle the operation and control system of microgrids and partly the monitoring and control layer. It is configured to have functions with long time scales, such as power generation forecasting, economic dispatching, and demand side management. It can have fast response times, usually involving data acquisition, system operation mode switching, black start, and emergency control.

4.4 Communication protocols and cyber security

4.4.1 Basic principle

The microgrid should have reliable information communication capabilities. The communication protocol and communication medium should be configured according to the specific application scenarios, real-time requirements, and the actual situation on site.

4.4.2 Recommended methods

The microgrid communication involves remote communication and local communication. The remote communication is applied for information exchange between the microgrid and the upstream grid dispatching system called "dispatch centre", and the local communication is applied for information exchange among MEMS, microgrid control and monitoring systems, DER and/or other internal equipment of microgrid. In the case of an isolated microgrid, i.e., it is not connected to an upstream main grid, there is no need for communication link with a dispatch centre (dotted point lines in Figure 3 and Figure 4).

The communication protocols shall be defined according to interoperability requirements. For example, the communication protocol can be the IEC 61850 series, IEC 60870-5-104, IEC 60870-5-101 and IEEE Std 1815.

For local communication, the number of layers depends on the structure of the microgrid management system.

Usually, a part of MEMS functions is carried out in the cloud, the communication can be based for example on Web Services REST protocols.

Local communication for structure 1: Stand-alone MEMS module

Under a three-layer architecture, the protocols of the IEC 61850 series, Modbus and other protocols can be applied between the microgrid controller and the DER and internal equipment of microgrid. The selected communication media of the microgrid can be optical fibre, twisted pair, wireless, etc. according to specific application conditions, see Figure 3.

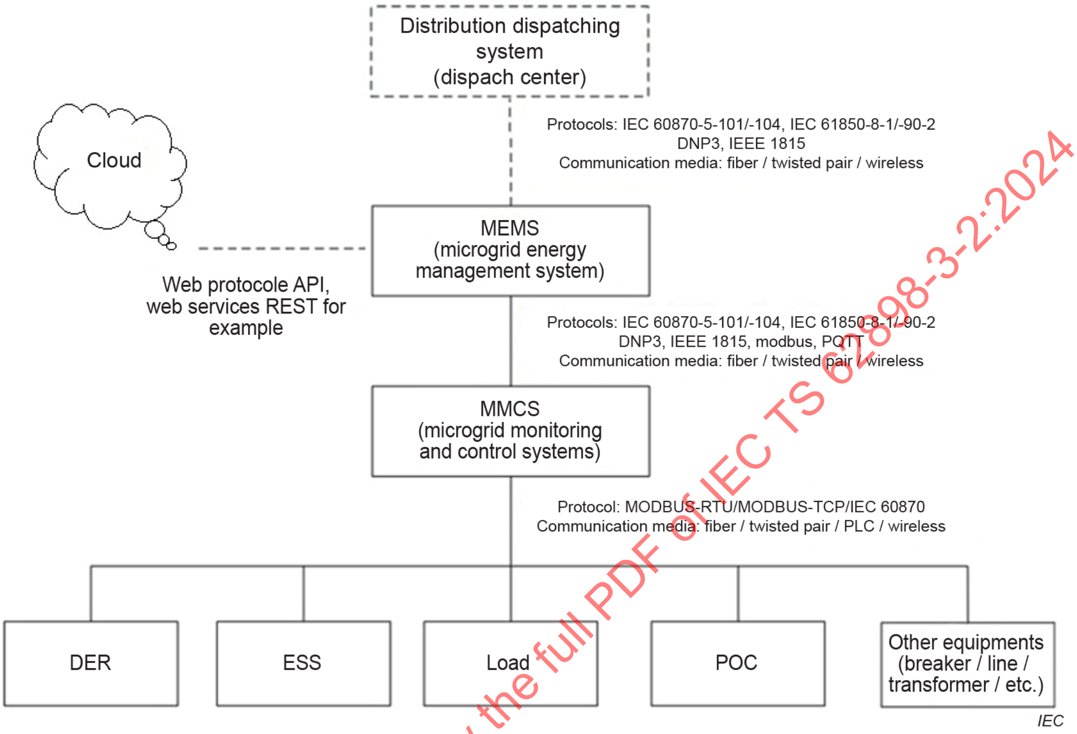


Figure 3 – Typical three-layer communication for structure 1

Local communication for structure 2: Integrated MEMS module

Under a two-layer architecture, the protocols of IEC 60870-5-101, IEC 60870-5-104, DNP3 (Distributed Network Protocol, IEEE Std 1815), etc. can be applied between MEMS and the microgrid controller, and the IEC 61850 series, Modbus and other protocols can be applied between the microgrid controller and the DER and internal equipment of microgrid. The communication medium used for the microgrid can be selected as optical fibre, twisted pair, wireless, etc. according to specific application conditions. For integrated MEMS modules, digital and analogue signals using I/O card could also be an option.

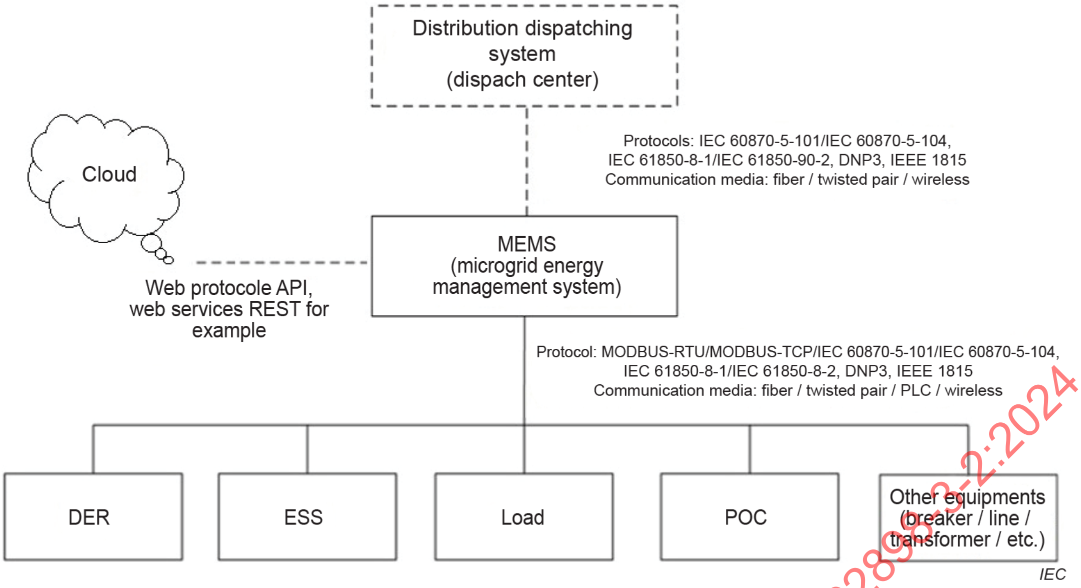


Figure 4 – Typical two-layer communication for structure 2

4.4.3 Cyber security

The cyber security strategy of MEMS shall be aligned with the IEC 62443 series, which defines security levels and associated requirements for Industrial Automation and Control Systems (IACS).

The IEC 62443 series defines four different security levels (SL1 to SL4), with specific requirements applicable to system level (see IEC 62443-3-3) and component level (see IEC 62443-4-2). The required level remains specific to each microgrid application and its required security profile. The manufacturer or system provider shall declare the security level of the MEMS and its components, as defined in the IEC 62443 series.

Cyber security functions of MEMS should be shared with MMCS (see IEC TS 62898-3-4), and the declared security level can be common.

4.5 Overview of MEMS function requirement

The configuration and main functionalities of MEMS shall be based on the selected type, purpose, use case, application, target and needs of the microgrid specified in IEC TS 62898-1.

The functionalities of MEMS can be chosen for reducing energy costs, optimizing generation assets, improving reliability, improving grid power quality, providing disaster-preparedness, demand side response. In islanding mode, the functionalities of MEMS can be set for providing power to remote areas with lower cost, improving reliability.

The functionalities shall be selected to always fulfil the main target of dispatch optimization considering the technical constraint conditions and selected optimization methods/sub-target modes.

The following optimization modes can be made available:

- economic dispatch optimization: energy costs reductions,
- environment dispatch optimization: CO_2 reduction,
- power quality/reliability/stability dispatch optimization: High power quality.

These optimization modes shall not be permanent. MEMS can select dynamically an appropriate optimization model according to the operating mode and system state. For example, when a grid-connected microgrid has abundant renewable energy, the optimization goal mainly focuses on the microgrid participating in the demand side response of the main grid to obtain higher returns. When the renewable energy resource is insufficient, the optimization target shall be switched to guarantee high power supply reliability with lower cost. When the grid-connected microgrid is switched to the islanding operation mode, the optimization goal shall be considered more on the power supply continuity of the critical load.

Besides the selected functions, MEMS shall integrate a common set of functional modules to accomplish the main target of dispatch optimization:

- forecast module: power generation and load forecast,
- power management module: load and generation coordinated control, active power control, reactive power and voltage control,
- alarm, security, safety module: dealing with emergencies,
- market module: market transaction and market data.

The implementation of the dispatch optimization target by the MEMS results into a unit commitment, power generation scheduling and power consumption plan, tie line of power plan, reserve plan/spare capacity. In the following parts of this subclause, the targets and functionalities are detailed.

Figure 5 gives the overall functional architecture of MEMS.

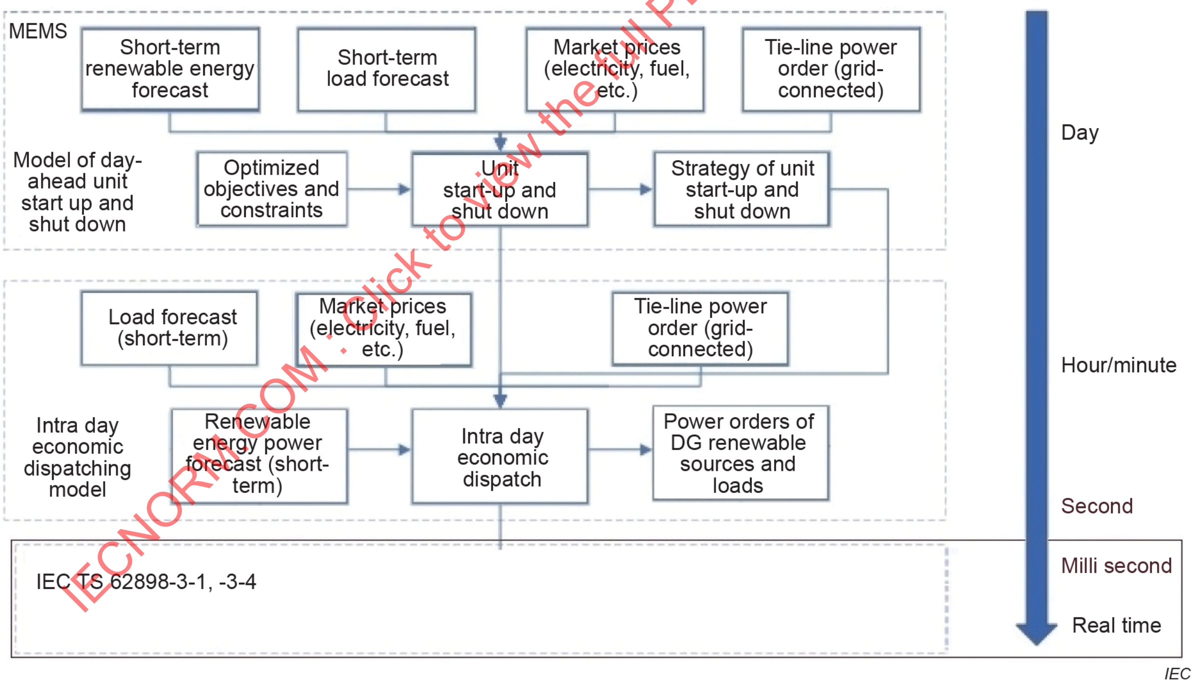


Figure 5 – Microgrid energy management system functional architecture

5 Functional requirements

5.1 Dispatch optimization

MEMS will optimize the generation dispatch mix of energy produced by all forms of DER generation, ESS storage and load consumption schedule, both electrical and thermal. For this, MEMS considers utility grid dispatching schedule, power forecasting, demand forecasts, renewable generation output, ESS charging/discharging states, real-time operating status, unit economic efficiencies, the energy import tariff and characteristics, constraints of generating resources and load.

The dispatch optimization results in safe, reliable, and economical optimal scheduling of the microgrid. Its goal is to minimize the economic cost according to the remote dispatch plan, power generation load forecasting data, real-time operation data of microgrid, power supply and load characteristics. MEMS should be able to provide such optimization up to a week in advance.

5.1.1 Dispatch and scheduling models

5.1.1.1 General

Scheduling models can be very different according to microgrid structures, optimization objectives and constraints.

Generation dispatch and load consumption schedule can be classified into day-ahead and intra-day (see 5.1.1.2 and 5.1.1.3).

5.1.1.2 Day-ahead economic optimization schedule

Economic dispatch should include day-ahead economic optimization scheduling. For instance, the economic optimization schedule can be based on 24 hours.

Day-ahead economic optimization dispatching should arrange a 24-hour unit combination plan, energy storage charge and discharge state plan, and a flexible resource power plan corresponding to the time scale from 00:00 on the next day.

According to the renewable energy output and the short-term power forecast of microgrid loads, day-ahead unit optimization start-stop model is used to optimize the microgrid: start-stop status of the sources, the switching plan of each type of load, the charge and discharge status of the energy storage systems, and SOC (state of charge) operation interval. The optimized scheduling plan is sent to the corresponding equipment and corresponding users in advance.

5.1.1.3 Intraday economic dispatch

The intra-day economic optimization dispatching will update the 4-hour power generation plan, energy storage charge and discharge plan, power consumption plan and flexible resource power plan from now on with a time resolution of no more than 15 minutes.

Based on the day-ahead schedule (start-up and shut-down plan of sources, switchable load start-stop status and SOC curve of PQ-type storage), the intraday economic plan can compute and optimize the operating powers of each sub-source and each load in the microgrid according to ultra-short-term power prediction results and the intra-day economic optimization scheduling model. Generation schedule can be generated manually or automatically with MEMS. The optimized scheduling plan is sent to the corresponding equipment and corresponding users in advance.

5.1.1.4 Real-time scheduling plan adjustment

Real-time scheduling adjusts planned power values in real time based on system and device security constraints and system operation.

5.1.2 Dispatch optimization modes and objective functions

5.1.2.1 General

The optimization of the dispatch is a target/objective function, which shall be specified by the microgrid owner whether to optimize generation dispatch based on economics, emissions, power quality, RES utilization or a combination of them. These objective functions are mainly based on user preferences, microgrid type, geographical location, installed equipment, microgrid capacity, policy orientation, electricity price, energy storage, and power generation.

Dispatch optimization is minimizing or maximizing a target/objective function, which shall be specified by the microgrid owner based on economics, emissions, power quality, RES utilization or a combination of them.

Dispatch optimization modes/objective functions/optimization goals of MEMS are also different according to the microgrid type being non-isolated or isolated.

The reliability and stability of a grid-connected microgrid is normally guaranteed with the external power grid as voltage and power support. Therefore, the priority shall be on economic dispatch optimization considering local power generation cost, as well as grid real-time electricity price and service market to achieve the most economical operation target. Economic optimization dispatching operation can reduce the cost of electricity and improve the power market revenue by optimizing the charging – discharging of the energy storage equipment, controlling the loads, scheduling the power supplies. Therefore, the optimization objectives of optimal dispatching for a grid-connected microgrid shall include:

- system operating cost, market revenue, planned value tracking error and other economic indicators,
- environmental cost,
- power quality, reliability and stability of the microgrid and the external grid,
- renewable energy utilization.

The primary task of isolated microgrid energy management is to ensure the long-term uninterrupted power supply of key loads in the microgrid and the safety and stability of its own real-time operation. On this basis, the economic indicators are considered, and the controllable part of the microgrid is optimized. The optimization objectives of optimal dispatching for isolated microgrid shall include:

- system operating cost,
- environmental cost,
- power supply reliability,
- renewable energy utilization, etc.

5.1.2.2 Economic dispatch optimization

The general economic optimization can be summarized as a cost reduction function, which considers operating costs, environmental costs, market benefit, and the economic goals that are converted by operating evaluation indicators with weighted coefficients.

The following variables can be taken into consideration in the economic dispatch optimization, where the list is not exhaustive. MEMS could propose part of them according to the targeted applications:

a) System operation costs including fixed cost and marginal costs:
   - power generation,
   - fuel,
   - distribution/transmission cost and potential upgrade cost,
   - maintenance,
   - start-up and shutdown,
   - equipment degradation,
   - power losses,
   - energy efficiency.
b) Environmental costs
   - carbon emissions with penalty costs.
c) Market profits
   - purchase from utility grid,
   - reserve capacity market profit,
   - demand response incentives,
   - day-ahead and real-time electricity market profit,
   - other grid service market profit.
d) Miscellaneous objectives
   - dissatisfaction costs,
   - reliability costs of microgrid,
   - tracking error penalties,
   - renewable energy utilization rate costs.

5.1.2.3 Power quality/reliability/stability dispatch optimization

The economic dispatch optimization shall reduce energy costs and jointly be implemented with the power quality dispatch optimization to deliver high power quality by optimizing the output of controllable DER for a safe and reliable operation of the microgrid.

5.1.2.4 Environment dispatch optimization: CO_2 reduction

Local regulation policy and environmental strategy can put CO_2 reduction into force. MEMS should set appropriate optimization goals and operation modes to improve the environment.

5.1.2.5 Renewable energy utilization optimization: high renewable energy utilization

In microgrids constituting renewable energy resources, the MEMS should be able to maximize the utilization of the renewable generation. While doing so, the MEMS shall be able to ensure the microgrid satisfies the stability and power quality requirements.

5.1.3 Management of technical constraint conditions

The economic optimization dispatching model of microgrid depends on diverse factors such as electrical structure, system composition and time scale. This results in different actual constraints. The general constraints mainly include unit output limitations, system operation constraints, robustness constraints, and constraints of other additional modules.

The following constraints should be taken into consideration in the economic dispatch functions:

a) Unit output constraints
   – maximum and minimum generation power and capacity of DER and EES,
   – minimum "down time" and "start-up time" of DER,
   – maximum ramp rate of DER,
   – start & stop or charge & discharge switching times of DER and ESS.
b) System operation constraints
   – generation-load balance,
   – power flow control,
   – reserved generation capacity,
   – environmental (emission) constraints,
   – exchange power at the point of connection (POC) between upstream grid and microgrid network,
   – small signal stability constraints,
   – power quality constraints,
   – system security constraints (power limitation of power lines),
   – power supply reliability constraints and probability of off-load state.
c) Robustness constraints
   – stochastic constraints of renewable energy power,
   – accidental cost constraints.
d) Miscellaneous constraints
   – controllable loads and other flexible resources constraints,
   – market behaviour constraints.
e) Safe operation constraint
   – constraints which guarantee the safe operation of microgrid.
f) Real-time operation constraints
   – unforeseen constraints.

5.1.4 Optimization types and approaches

Different constraints and optimization objectives form different microgrid economic dispatch optimization solving problems. The optimisation principle shall be declared by the MEMS manufacturer and a non-exhaustive list of optimization methods shall be given as an example with the necessary explanations. The types of optimization solving problems are mainly divided into:

- mixed integer programming problem,
- dynamic programming problem,
- stochastic and robust programming problem,
- non-linear programming problem,
- non-differential programming problem,
- multi-objective programming problem.

According to the different problems of economic dispatch optimization, different specific optimization methods can be used to solve actual problems quickly and effectively. The optimization calculation methods mainly used are:

- heuristic approach,
- agent based approach,
- evolutionary approach,
- model predictive control approach (MPC method),
- neural network approach,
- other artificial intelligent approach.

5.2 Forecast function

5.2.1 General

Forecasts in the microgrid include power generation forecasting, load forecasting, and electricity price forecasting.

MEMS shall include the forecast module (power generation and load forecast) taking into consideration external and internal factors. External factors include environmental conditions (e.g. geography, meteorology, resources, etc.), requirements on economy and reliability, and structure and voltage level of distribution network where microgrid is connected. Internal factors include type and characteristics of DER, capacity and site of ESS, characteristics and requirements of load, structure of microgrid network, and control strategy.

MEMS shall be capable of receiving forecasted data of power generation and load or carry out autonomously generation power forecasting based on historical meteorological measurement data and weather forecast data as input data.

5.2.2 Forecasting requirements and time dimension

A variety of algorithms should be established to form a library of prediction algorithms, and the algorithm parameters should be appropriately adjusted according to regional and seasonal changes, and the differences between normal days and holidays should be considered.

Forecast module can have short-term, ultra-short-term photovoltaic power generation, wind power generation, and load power prediction functions. The following time resolution values are given as examples, they can be different according to applicative requirements for each region, country, or use case.

The short-term forecast can give daily start time and sequence number of forecasts, support automatic start and manual start, and predict the data of the next 1 day to 3 days; the data time scale is 15 minutes.

Ultra-short-term forecasting can be predicted every 15 minutes with automatically rolling execution, and is able to predict data for the next 15 minutes to 6 hours.

The power generation forecast model can predict the power generation at different time scales. The type of forecast involved in MEMS is generally short-term forecast with a time horizon less than a week.

5.2.3 Renewable power generation forecast

Specially, for microgrids with intermittent generation resources such as wind power, solar power, MEMS should incorporate a supervisory and measuring function on generation resources and a forecasting function on power generation at various time scales. Power generation forecasting is mainly based on the prediction of wind and photovoltaic generation. When other power generation units such as tidal energy, wave energy, geothermal energy, etc. are installed, the relevant prediction function should be configured. IEC TR 63043 gives detailed information such as renewable energy power forecasting at different spatial and temporal scales, and the forecasting technologies for wind and photovoltaic powers.

Power generation forecasting is the basis for microgrid planning and operation. Based on historical measurement data, actual weather forecast data and real-time operational data, the power level of different power generation units at different time scales is predicted. Renewable power generation predictions in microgrids are generally divided into photovoltaic predictions and wind power predictions.

5.2.4 Load forecast

The load forecast function utilizes historical load data as well as seasonal weather conditions to forecast load profiles for the site at various time scales. The forecasting object includes future power demand (power) and future power consumption (energy) and prediction of load curve.

Load forecasting should have short-term and ultra-short-term load prediction functions focusing on the hourly system load. In the microgrid system with integrated multi-energy function, it should be equipped with relevant cold and heat load forecasting.

When industrial loads are present, load forecast should include plant process forecast. This is typically associated with the production planning, and includes maintenance cycle, load variation associated to the manufacturer process, etc.

5.2.5 Electricity price forecast

Electricity price forecasting should have a power price prediction function to assist load management and demand side response functions.

5.2.6 Input values of forecast

The input value of forecast can include information in the area where the microgrid is located:

- latitude, longitude, and altitude,
- historical generation and load data,
- weather type such as temperature, humidity, precipitation, sunshine, wind level, wind direction, pressure,
- historical electricity price information.

<u>For PV generation:</u> PV installed capacity, PV cell type, PV installation angle, inverter type (AC or DC coupled), PV module level maximum power point tracking (MPPT) optimization, tracking mode, PV module area and quantity, characteristic curve. Historical and real-time data of photovoltaics, including but not limited to: photovoltaic active power, starting capacity, working state, photovoltaic power generation fault record, total radiation, direct radiation, scattered radiation, photovoltaic module temperature, photovoltaic ambient temperature, humidity, air pressure, wind speed and wind direction, variable export limiting.

<u>For wind generation:</u> wind turbine installed capacity, hub height, blade diameter, power curve and other data. Historical and real-time data of wind measurement including but not limited to average wind speed at 10 m, 30 m, 50 m, average wind direction, maximum wind speed and wind speed standard deviation, average pressure at 10 m height, average temperature, and average humidity.

5.3 Demand side integration

5.3.1 General

The MEMS can include a demand side integration strategy such that it is focused on ensuring the efficient and effective use of the microgrid or external grid.

Demand side resources are resources on the customer side of the meter that can be relied on to respond to market conditions of the microgrid or external grid. This can include distributed generation, storage, dispatchable load and other on-site resources capable of impacting demand for the microgrid.

5.3.2 Demand side management

Demand side management is the process where the MEMS can control loads and storage systems in order to manage demand. With direct load control, customers' load and storage is controlled in accordance with agreed criteria. The microgrid demand side management should be carried out on the basis of internal load characteristics, such as critical load, reducible load, interruptible load, transferable load, etc., combined with system economic operation strategy or auxiliary service requirements to develop various types of load control methods at different time scales to ensure economical and reliable operation of the microgrid or external grid.

MEMS can classify loads by taking user's requirement on reliability, impact on personnel safety, microgrid safety, economic loss caused by power interruption into consideration. On the base of load classification, load control strategy and schedule under various operating conditions can be determined in advance. MEMS can be capable of managing load in accordance with real-time load monitoring data, and power usage schedule. In island mode, MEMS can be capable of implementing load shifting strategies on load terminals. Load shifting strategies include control turns, time duration, power setting, energy setting, etc. Load shifting strategies are distributed to central controller to execute. Load shedding is managed by MMCS (IEC TS 62898-3-4).

5.3.3 Demand side response

Demand side response is related to load shaping and refers to a set of strategies which can be used to increase the participation of the demand response provider or end-use customers, in setting prices and clearing the market. Demand response functions include but are not limited to program management, demand side resource management, and event management.

Program management: MEMS can set up a demand response program in accordance with the requirements of the demand response provider. Demand response strategy can be updated with real-time power generation cost, component conditions and power consumption. Outdated demand response program should be deleted.

Demand side resource management: MEMS can acquire and maintain information of demand side resource, such as critical loads, non-critical loads, remote controllable loads, interruptible loads. On the base of the operation condition of demand side resources, MEMS can provide optimal operating strategy. Demand response potential can be analysed for controllable and uncontrollable resources.

Event management: MEMS can release a demand response program to the demand response provider. For example, if microgrid operator provides a price-based demand response program, MEMS can release electricity rates for the period during which the demand response is required. Assessment and settlement can be carried out to evaluate the rationality of the demand response program and settlement in accordance with the demand response contract.

5.3.4 Energy optimisation

MEMS should monitor power consumption condition of key loads and work out load characteristics and energy optimisation characteristics on the base of acquired data, such as power, energy, peak hour, off-peak hour, coincidence, density, etc. MEMS should improve economy and efficiency of power supply while ensuring power supply reliability. On the base of day-ahead power generation forecast and load forecast, day-ahead optimized strategy is established. Real-time energy optimisation management is dynamically adjusted using day-ahead optimized strategy while taking electricity price, real-time power generation and load demand into consideration.

5.3.5 Power and energy exchange with upstream grid

MEMS should exchange power and energy with the upstream grid according to the dispatching agreement signed. The energy exchange could be bidirectional, and it can be driven by auxiliary services or a supplementary supply of the grid to the microgrid.

5.4 Flexible resource management

5.4.1 General

The flexible resources in the microgrid include energy storages and controllable loads. The role of flexible resources in the microgrid can be divided into two categories according to the interaction microgrid – main grid and microgrid internal coordination. When considering the interaction of microgrid – main grid, the microgrid is considered as a whole body which exchanges energy with the main grid and assists the main grid to complete the demand side response related function by adjusting the energy storage and controllable load. During the internal coordination of the microgrid, the adjustment of the energy storages and the controllable loads can reduce the impact of the prediction error on the operation of the microgrid and provide a fast power response when the power generation and load are largely unbalanced and improve the reliability of the system operation.

The assistance of flexibility resources for microgrid to participate in the demand side response includes but is not limited to the following items:

a) Price-based demand response
   – real time pricing,
   – time-of-use tariffs,
   – critical-peak pricing.
b) Incentive-based demand response
   – interruptible/curtailable service,
   – direct load control,
   – emergency demand response,
   – capacity market,
   – demand bidding/buyback.
c) Demand side ancillary services
   – non-rotating reserve,
   – rotating reserve,
   – frequency regulation,
   – voltage and reactive power regulation.

5.4.2 Controllable load management

The management of the controllable load by the microgrid energy management system includes but is not limited to the following:

a) In grid-connected operation mode, the load is shifted according to the electricity price curve to obtain the maximum benefit.

b) In grid-connected operation mode, the load is shifted according to the period of renewable energy production to obtain a maximal local use of the locally produced energy.

c) In islanding operation mode, load shifting is performed according to the load prediction result to balance power generation and demand load.

d) In islanding operation mode, it determines the priority and scheme of load shedding, and performs load control operation to ensure stable operation of the microgrid when power generation and load are largely unbalanced.

5.4.3 Energy management

Microgrid energy management system includes but is not limited to the following actions:

a) In grid-connected operation mode, the control of charge and discharge of energy storage is performed in function of one of the following objectives:
   - cost optimization (in function of the electricity price and cost of charge),
   - optimization of the renewable energy sources for local use (in function of the power demand and the local renewable energy use),
   - power peak shaving strategy (in function of the power demand).

b) In islanding operation mode, it controls the energy storage charge and discharge according to the load prediction result and the energy storage charge and discharge cost to balance power generation and load demand.

c) In islanding operation mode and in emergency situations, it determines the energy storage charge and discharge scheme and performs rapid charge and discharge operations to ensure stable operation of the microgrid when power generation and load are seriously unbalanced.

d) According to the operating state of each energy storage (not only limited to state of charge (SOC) and state of health (SOH), it decomposes the total power control instruction of energy storages and distributes dedicated power and energy controls to each individual energy storage unit.

5.5 Data archiving, trending and reporting

MEMS shall be capable of receiving data from MMCS.

5.6 Market trading module (ancillary services) and market data

The microgrid can effectively participate in the electricity market in the form of ancillary services according to electricity prices or incentive policies in order to achieve bidirectional security and economic guarantee. The microgrid can provide support services such as rotating reserve, frequency modulation and black start auxiliary power supply, and the upstream power grid can provide spare capacity for the microgrid under some fault operation modes.

Dedicated market trading module is designed for offering ancillary services in the countries where the electricity market has been established.

Annex A
(informative)

Examples of actual microgrid application cases integrated with associated functions of MEMS

A.1 General

All the following application cases are mainly focused on MEMS functions. However, other functions related to MMCS such as operation mode management and black start are also included to give a complete overview of the application cases.

This annex provides 11 application cases from 5 countries to introduce the MEMS applications in various scenarios. As background information, some company and/or organization names are mentioned, including: Goldwind, MAN ES, NEDO, ANRE, METI, Okinawa Electric Power Co., Inc. QEERI, OTF, QEERI/QF. These trade names are given for the convenience of users of this document and do not constitute an endorsement by IEC for the projects and/or service of these companies.

A.2 Application CN1: Obtaining lower energy cost, lower pollution emission, and higher penetration level of renewable energy

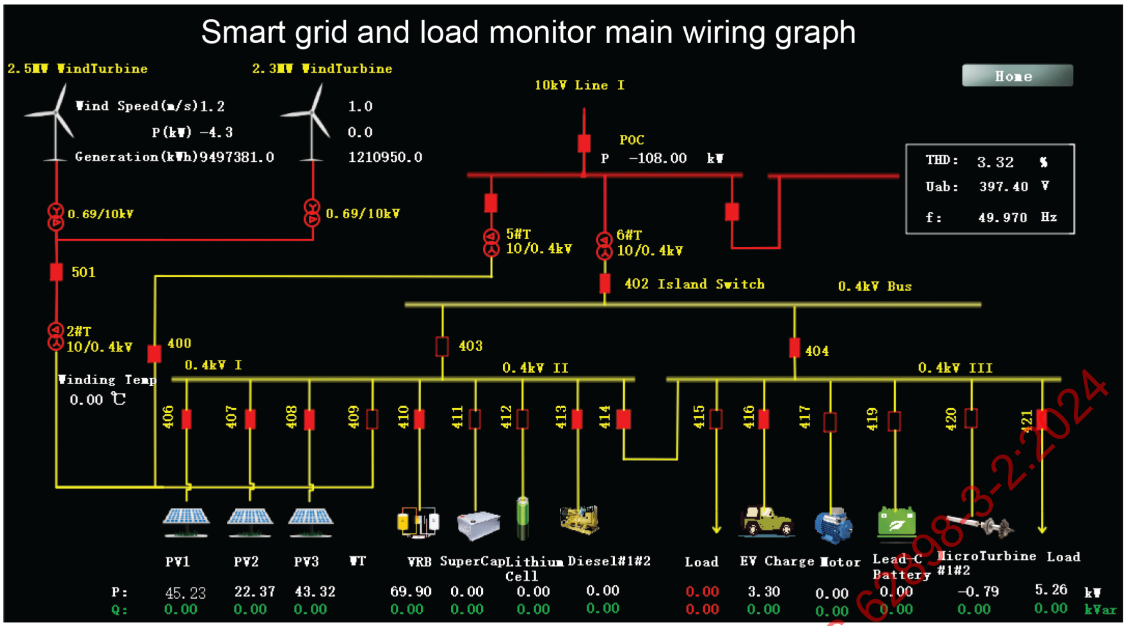
A.2.1 Overview

The microgrid project is located in the Goldwind [1] Smart Campus, Yizhuang Economic–Technological Development Area, Beijing, China. There are assembly lines, office buildings, a big data centre, a culture and sport centre, electric vehicle charging stations, etc. All year round, the campus has demands for electric power, cooling and heating. The microgrid includes multiple distributed energy sources. The project was officially put into operation in 2012.

A.2.2 System structure

The main single line diagram of the Goldwind microgrid is shown in Figure A.1. The Goldwind microgrid is a non-isolated microgrid with high renewable penetration ratio. The total installed capacity of renewable energy sources is 5,8 MW. It includes 4,8 MW wind turbines and 1 MW PV. The microgrid is composed of 665 kW microturbines, 276,0 MWh energy intensive EES and 900 kW ×10 s super capacitors. More than 75 % of the power demand of the campus is supplied by the local DER in the microgrid.

1 "Goldwind" is provided to illustrate the location of the microgrid project, which is located in the Goldwind campus. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC.



Source: Key Technology of Industry Park Energy Internet Protection and Control" of Goldwind internal report, Dec. 2018. Goldwind of China has kindly authorized the use of the above figure.

Figure A.1 – The main single diagram of Goldwind microgrid

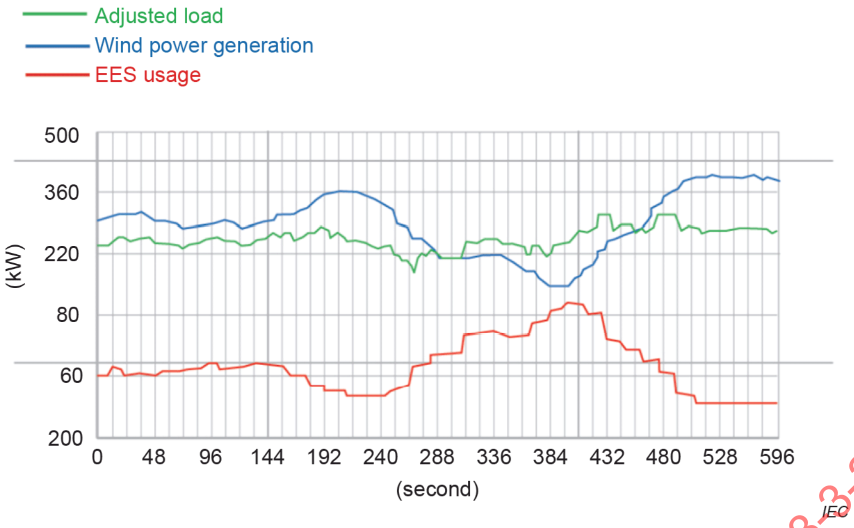
A.2.3 Energy management system

When the circuit breaker at the POC is open, the microgrid starts to operate in island mode. The energy management system of the microgrid includes the forecasting modules for the wind generation, PV generation and load demand. The supply-demand power balance of the microgrid can be achieved by controlling the charging and discharging state and power of the energy intensive EES. The objectives of the MEMS are to achieve the lowest energy cost, the lowest pollution emission, and the highest utilization rate of renewable energy. Factors such as generation and energy storage costs, power limits of generation units, power price, user requirements of power quality, demand response, pollution emission and others are taken into consideration.

A.2.4 Energy management system operation

The MEMS is designed to achieve the following functions when the microgrid is in grid-connected mode:

- The optimal operation plan is formulated and executed according to the real-time electricity price, and the forecasted wind generation, PV generation and load.
- Charging-discharging of the EES is controlled according to the state of charge (SOC) of the EES, real-time electricity price and others. For instance, when electricity price is high, EES shall not be charged from the utility grid to avoid high cost. When electricity price is low, EES can be charged to store energy for future use.
- The EES is also used for peak shaving and valley filling according to the forecasted wind generation, PV power generation and load. For instance, as shown in Figure A.2, when the power generation from the DER is not enough to supply the load (shown as a dip in the wind power generation curve in Figure A.2), the EES is used to compensate the gap and ensure the power balance.



Source: Key Technology of Industry Park Energy Internet Protection and Control" of Goldwind internal report, Dec. 2018. Goldwind of China has kindly authorized the use of the above figure.

Figure A.2 – Application of EES for wind generation and load matching

The MEMS is also designed to achieve the following functions when the microgrid is in island mode:

- The charging-discharging of the EES is controlled to supply the load demand and to ensure the power and energy balance. It is significant to keep the power balance in island mode.
- The loads in the microgrid are classified based on their significances. Critical loads are ensured the highest priority and reliability during the island mode. Non-critical load shedding could be implemented by the MEMS depending on the generation, load, and the SOC of the EES.

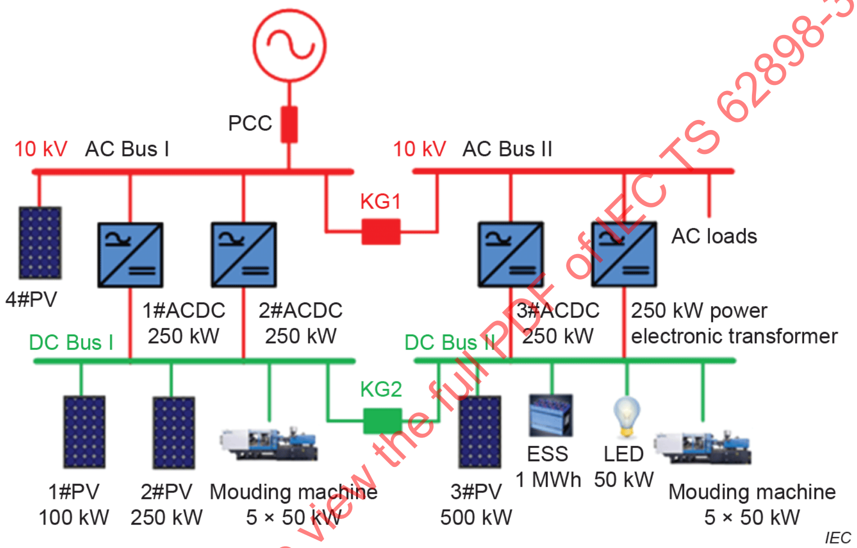
A.3 Application CN2: Enhancing local power supply reliability for critical loads with AC/DC hybrid microgrid

A.3.1 Overview

Shangyu AC-DC Microgrid Project is located in Century Huatong Industrial Park, Shangyu Economic Development Zone, Shaoxing City, Zhejiang Province, the People's Republic of China. There are many automobile plastic parts plants in the park. The production load is mainly DC plastic injection moulding machines. The peak load power is important, and the plant requires high reliability of the power supply of upstream power grid. The project was officially put into operation on 26 August 2017. The load in the plant can directly use the clean electric energy generated by the distributed power supply through the DC bus. This reduces the multi-level conversion of the original DC to AC to DC and improves the energy utilization efficiency. With the help of the microgrid energy management system, the high-proportion distributed power supply is designed to be efficiently absorbed on the site itself, and the economical operation of the system is improved. In case that external power grid fails, the power supply of some important loads is ensured by the microgrid.

A.3.2 System structure

The topological structure of Shangyu AC-DC hybrid microgrid is shown in Figure A.3. It belongs to grid-connected microgrid type. The microgrid is connected to the upstream distribution grid through PCC. The whole microgrid adopts a multi-AC/DC bus-bar hybrid structure: the AC side is divided into two-section bus bars I and II, the rated voltage is 10 kV, and is connected by AC bus bar separation switch KG1. The DC side is also divided into two-section bus bars I and II, the rated voltage 560 V, connected by DC breaker KG2. Power exchange between the AC and DC systems is achieved by three 250 kW AC/DC power flow controllers in parallel and one 250 kW power electronic transformer. The AC side load is mainly the auxiliary load and some other existing load in the plant. The 1 500 kW distributed PV generation is also connected to 10 kV AC bus. The DC load of the microgrid mainly includes 10 plastic injection moulding machines (10 × 50 kW), LED lighting (50 kW) and 4 electric vehicle charging piles (4 × 60 kW). The DC bus bars are also connected to 850 kW DC PV generation, which is equivalent to the load capacity, and one 250 kW/1 MWh lead carbon battery energy storage system.



Source: Internal technical report for the National High-tech R&D Program of China (863 Program) Project "The key technology of high-density distributed energy access to AC-DC hybrid microgrid", Dec. 2018. State Grid Zhejiang Electric Power Co. Ltd. has kindly authorized the use of the above figure.

Figure A.3 – Electric network topology of Shangyu AC/DC microgrid

A.3.3 Energy management strategy

Shangyu AC-DC hybrid microgrid belongs to the grid-connected microgrid. When the switches KG1 and KG2 are disconnected, the right half part of the system forms a small independent AC-DC microgrid with short-term islanding operation capability.

For grid-connected operation mode, the energy management strategy is modelled with consideration of the randomness of the wind and PV resources, the uncertainty, and the master-slave modelling method. The objective function of the main model is to maximize the utilization of distributed renewable energies and the constraint condition is mainly the distributed power supply output limitation. The objective function of the slave model is to minimize the system network loss and the storage energy loss. The constraints include AC/DC and other equipment output limitations, energy storage constraint, energy balance, conversion efficiency, power limitation at PCC, DC side power balance, and AC side power balance. The chaotic binary particle swarm optimization algorithm is used to obtain the optimal solution of the model.

For off-grid operation mode, the energy management strategy is also modelled by using the uncertainty master-slave game modelling method. The objective function of the main model is to maximize the utilization of the distributed energies. The constraint condition is the distributed power supply output limitations. The objective function of the slave model is to minimize the system network loss, the energy storage loss and the cost of interruptible loads. The constraint conditions include the DC side power balance, AC side power balance, AC/DC equipment output limitations, energy storage output power and current limitations. The chaotic binary particle swarm optimization algorithm is used to obtain the optimal solution of the model.

A.3.4 Operation modes

According to the opening and closing state of the busbar separation switch, Shangyu microgrid system can be divided into four operation modes: 1) KG1 and KG2 are closed: grid connection mode; 2) KG1 is opened, KG2 is closed: AC segmentation mode; 3) KG1 is closed, KG2 is opened: DC segmentation mode; 4) KG1 and KG2 are opened: islanding operation mode. The energy management system can judge the present operating mode according to the switching state of the system, and automatically adopt a relevant control strategy.

When the system is in grid-connected and DC segmentation mode, the energy management system's control objectives are:

- According to the prediction curve, the actual electricity price and the present output, the optimal operation plan is formulated, the system comprehensive operation cost is minimized, and the utilization of distributed power source is maximized.
- According to the SOC state, energy storage participates in the tie-line power control adjustment, and optimizes the purchase and sale of power with upstream main power grid.
- Energy storage SOC management and adjustment of SOC should be in a reasonable interval. At this stage, the main task of energy management system is to ensure the economic operation of the system.

When the system is in AC segmentation mode, the control objectives of the energy management system are:

- According to the prediction curve, the actual electricity price and the present power output, the optimal operation plan is formulated, the system comprehensive operation cost is minimized, and the distributed power utilization is maximized.
- Energy storage SOC management and adjustment of SOC should be in a reasonable range. There is no longer participation in tie-line power control adjustments.

When the system is in island operation mode, the energy management system has the following control objectives: 1) reliable power supply to the right half part of the system to ensure power balance in the AC and DC areas; 2) photovoltaic power limitation to prevent system crash when the photovoltaic power is much larger than the load; 3) Interruptible load control, priority to ensure important load power supply.

A.3.5 Black start

For the right half part of the microgrid, a black start strategy is designed, with automatic and manual start modes. Before a black start, it shall confirm that KG1 and KG2 switches are disconnected, that there is no voltage on the AC bus bar II and DC bus bar II, and that all devices are in the stop state.

Manual black start mode: 1) start the energy storage converter, establish the DC bus II voltage; 2) start the #3 AC/DC converter, establish the AC bus II voltage; 3) start the electronic power transformer; 4) start the photovoltaic power generation; 5) Connect AC and DC loads; 6) Confirm that the whole system is working properly.

Automatic black start mode: Click the black start button. After the system is started, confirm whether the system is working normally.

A.3.6 Energy management strategy

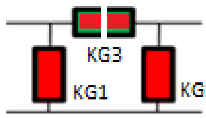
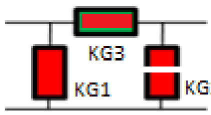
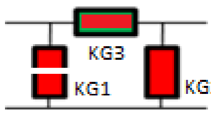
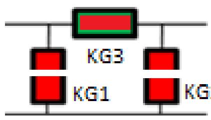
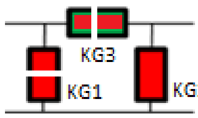
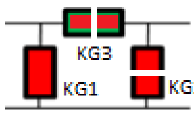
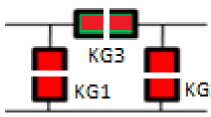
The power supply system in Nanji Island is an off-grid microgrid. The main control objectives of the energy management system are: 1) reliable power supply to the system; 2) maximum utilization of renewable energy; and 3) minimum management of energy costs for the whole system. The specific performance is summarized hereafter:

- Through the wind, solar and load forecasting, the number of start and stop of the diesel generator is arranged by rolling optimization algorithm in order to ensure the system power balance. The diesel power supply is reduced by maximizing the utilization of clean energy.
- Use the hybrid energy storage system to stabilize the fluctuation of renewable energy output. The super capacitor is used for rapid power stabilization, and the battery energy storage is used for energy fluctuation.
- Load grading management. The system load is divided into critical load, general load and adjustable load. In an emergency situation, MEMS adjusts the adjustable load power of electric vehicles, building air conditioners, hotels, etc., and prioritizes the supply of critical loads. The electric vehicle charge is generally arranged in the middle of the night where there are more wind resources and lower residential load.

A.3.7 Operation modes

The three fast switches KG1, KG2 and KG3 in Nanji Island microgrid divide the whole system into seven operating modes (as shown in Table A.1).

Table A.1 – Operation modes

	Operation modes	**631 sub microgrid**	**632 sub microgrid**	**Main power sources**	**State of switch**			**Scheme**
					KG1	**KG2**	**KG3**	
1	Economical energy Whole microgrid (KG1-KG2)	Grid connected	Grid connected	Diesel generation	ON	ON	OFF	
2	Economical energy Whole microgrid (KG1-KG3)	Grid connected	Grid connected	Diesel generation	ON	OFF	ON	
3	Economical energy Whole microgrid (KG2-KG3)	Grid connected	Grid connected	Diesel generation	OFF	ON	ON	
4	Green operation mode Whole microgrid	Grid connected	Grid connected	Energy storage	OFF	OFF	ON	
5	Economical energy Sub-microgrid (KG2)	Islanded	Grid connected	Diesel generation	OFF	ON	OFF	
6	Economical energy Sub-microgrid (KG1)	Grid connected	Islanded	Diesel generation	ON	OFF	OFF	
7	Green operation mode Sub-microgrid	Islanded	Islanded	Energy storage	OFF	OFF	OFF	

The energy management system shall automatically choose the relevant control strategy according to the present system operating mode. Different operating modes shall switch among different main power supply sources. Before the planned mode is switched, the energy management system performs the necessary calculations, taking into account the local switching device to ensure that the system has a sufficient stability margin during the switching process.

A.3.8 Black start

According to the main power supply, the Nanji Island microgrid is equipped with two kinds of black start modes, namely, the black start with diesel engine and the black start with energy storage. The combination of automatic procedure control and manual confirmation ensures the fast recovery of the system power supply.

Before a black start, it shall confirm that there is no voltage on the AC bus and that all devices are in the shutdown state.

Sequence of diesel generation based black start:

- start diesel generation and establish bus voltage,
- start energy storage inverter,
- progressively switch on the loads,
- progressively switch on the decentralized power generations.

Sequence of energy storage based black start:

- start energy storage inverter and establish bus voltage,
- progressively switch on the loads,
- progressively switch on the decentralized power generations. After starting up the whole system, verify that all components are in good operation state.

A.4 Application DE1: Intelligent, data-driven, and grid stabilizing energy management platform – Developing a pilot for industrial diesel application

A.4.1 Overview

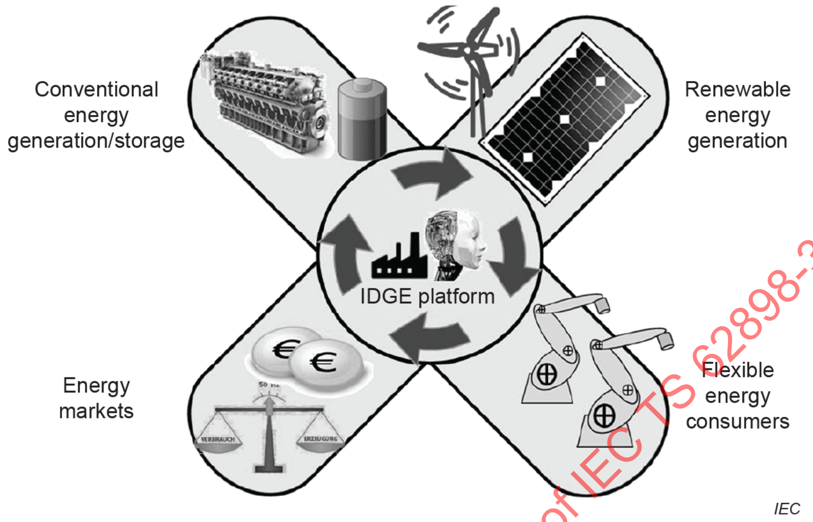
The increasing abandonment of nuclear and coal-fired power plants as well as the expansion of photovoltaic and wind power plants are current trends in power generation worldwide. In particular, the growing share of renewable energy sources is increasingly endangering the security of energy supply and leads to strong fluctuations of electricity prices. This poses enormous challenges especially for industrial companies, as rising and strongly fluctuating energy costs have a negative impact on their production costs. Therefore, intelligent energy management solutions are needed which integrate self-generation, energy storage, external power purchase, and flexible consumption.

Against this backdrop, MAN ES is currently developing an intelligent, data-driven, and grid-stabilizing energy management platform (IDGE Platform) for utility-scale customers. For energy production, the IDGE Platform is able to integrate conventional, e.g., diesel or gas gensets, and renewable energy generation, e.g., photovoltaic systems PV and wind turbines WT, in combination with energy storage BESS, e.g., lithium-Ion batteries. Moreover, the platform connects flexible consumers and offers an optional interface to power and energy markets. In order to optimize the generation from an economical perspective and maintain a balance with consumption, we developed and implemented an optimization algorithm which aims to increase power quality, i.e. grid stability, and to reduce the generation costs. Our work is part of a publicly funded project.

A.4.2 System structure − IDGE Platform

A.4.2.1 Layout of the IDGE Platform

The overall aim of the IDGE Platform is the integration of onsite-generation, external power and energy procurement, and flexible consumption (see Figure A.4) to enable intelligent energy supply and consumption.



Mr. Juan-Carlos Mejia has kindly provided the above figure.

Figure A.4 – Basic structure of the IDGE Platform

The energy supply is to be controlled via standardized interfaces to energy markets, own onsite generation plants, and energy storage facilities. The energy consumption is controlled via interfaces to machines, production infrastructure, energy storage facilities and external consumers. Speed and flexibility of generation as well as flexibility of consumption is offered on control power markets. The core of the IDGE Platform is a linear optimization algorithm that uses all integrated functionalities to automate and enable intelligent, data-driven, and grid-stabilizing energy supply management in real time. In this work, we focus on the optimization of self-generation.

We chose a modular platform structure for enabling an easy integration of additional modules regardless of the respective application context. To ensure grid-stability and cost-efficient energy supply, the platform evaluates sensor data of connected modules. Based on this data input, the optimization algorithm calculates the optimum share of available energy modules to meet the current demand. Thereby, the platform reduces complexity for human users and provides decision support and recommendations for the control of the power plant in real time. The user interacts with the IDGE Platform via special user interfaces, which allows for setting a context-specific target functions and requirements.

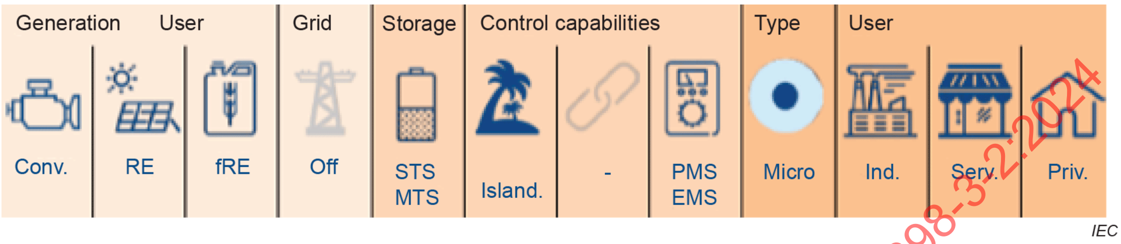
Plant operators can monitor and control the following key parameters for power quality:

- frequency,
- active power generation and demand,
- voltage,
- reactive power generation and demand,
- power-factory generation.

Plant operators can monitor the following key parameters for economic optimization:

- current generation costs,
- marginal generation costs,
- fuel price,
- wholesale power and energy prices.

A.4.2.2 Functional requirements, operating modes and use cases



Mr. Juan-Carlos Mejia has kindly provided the above figure.

Figure A.5 – Functional requirements

Based on market requirements (see Figure A.5), certain use-cases for hybrid and microgrid applications have been identified: fuel saving, peak shaving, spinning reserve, ancillary services, power arbitrage, enhanced dynamics.

Looking at the use-cases and customer requirements, MAN identified six archetypes, describing a path of de-carbonization by enhancing RES-penetration for off-grid and grid-parallel operations. Those archetypes will lead the way to an up to 100 %-RES world.

- archetype 1: Microgrid with conventional generation and strong grid-connection,
- archetype 2: Conventional-hybrid-plant with strong-grid-connection,
- archetype 3: Microgrid with conventional backup-power and weak-grid-connection,
- archetype 4: Microgrid with conventional generation and weak-grid-connection,
- archetype 5: Microgrid with conventional and RES-generation without grid-connection,
- archetype 6: Microgrid pure RES-generation and storage without grid-connection.

Depending on the specific application and configuration, the IDGE platform can operate in the following modes:

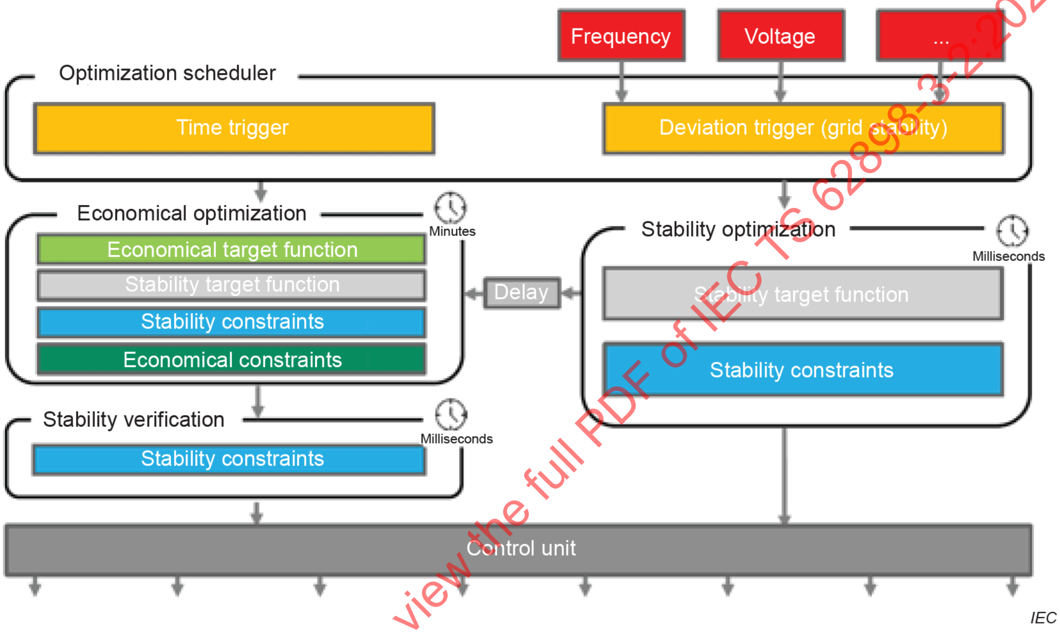
- supply to grid,
- supply from grid,
- island (generator),
- island (no generator),
- black start,
- unintentional grid outage (generator),
- unintentional grid outage (no generator),
- intentional grid outage (generator),
- intentional grid outage (no generator).

A.4.3 Energy management strategy

A.4.3.1 Optimization algorithm

The aim of the optimization is to ensure the operator's interest from a business point of view to reduce costs and maximize revenues. The basic prerequisite, however, is a stable operation (in terms of frequency and voltage stability) of the microgrid.

An integrated optimization, which both 1) ensures grid-stable operation of the microgrid and 2) minimizes the costs of power generation. For this purpose, two separate optimization models were developed, see Figure A.6. The interaction of both enables intelligent control of the overall system:

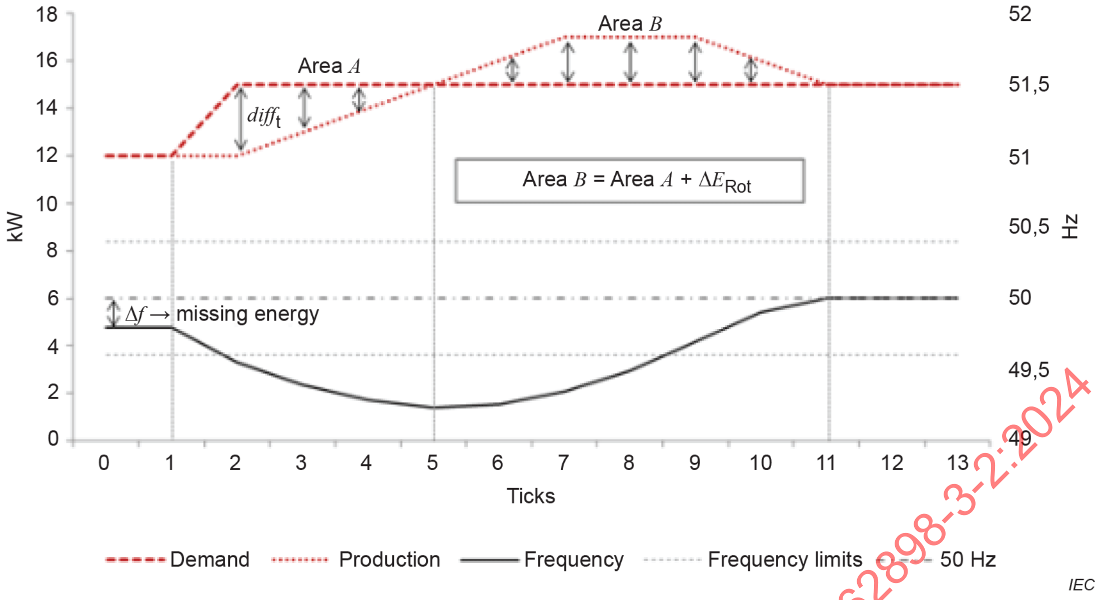


Mr. Juan-Carlos Mejia has kindly provided the above figure.

Figure A.6 – Interplay of Layer 1 and Layer 2

A.4.3.2 Grid stability – Layer 1

As a prerequisite for economic optimization, a grid-stable optimization model was developed, which reacts to short-term changes in the state of the grid, which are triggered by any deviation from the dead band set points for frequency and voltage. No economic factors are included in the grid-stable optimization. The primary objective is to restore grid stability as quickly as possible. In order to enable calculation in near real time, only grid-stable restrictions are considered and supplemented by a target function for grid stability. In addition, the model is limited to a linear optimization model in order to keep the runtime low and to meet the requirement of a near real-time calculation. Once the calculation has been completed and the recommended course of action has been passed on, the economic optimization is initiated. If both optimizations are completed at the same time, the grid-stable optimization is always prioritized. Figure A.7 summarizes this procedure. In the further course of the document, the economical and grid optimization are considered as one integrated model, unless explicitly stated.



Mr. Juan-Carlos Mejia has kindly provided the above figure.

Figure A.7 – Model reaction

A.4.3.3 Economic optimization – Layer 2

The economic optimization consists of a target function that takes into account different cost factors of energy generation. The target function should always be minimized, which means that an economically optimal solution is also the most cost-effective. Thus, Layer 2 mainly consists of the calculation formulas for all cost factors. It is optional to apply economic restrictions as well, e.g., to limit the costs of individual system components. Cost factors are the battery charging, the genset fuel and resource consumption and maintenance, and energy shortage. Photovoltaics and wind power will be added at a later stage of the project.

Layer 2 compares grid-stable solutions from an economic perspective. Each solution implicitly provides values for the power of the engine, how much energy the battery is charging or discharging, and how many loads have to be dropped. These values are used as input for Layer 2 as they represent the main cost drivers. However, the calculations of the battery and engine costs are more complex and can be divided into several areas.

An engine generates costs by consuming resources, due to wear and tear, and due to emissions. Fuel consumption is the most expensive component, but we also consider lubricating oil, urea, starting resources such as starting air, and other auxiliary materials. Wear and tear costs relate to individual parts of the engine and the current power that periodically either shall be replaced or serviced. Some components shall be serviced or replaced after a certain number of starts or after a certain number of operating hours. In practice, wear and tear costs only occur if a part has to be serviced or replaced. In the model, however, we have to compare different engine loads within limited periods of time and, hence, have to compare wear and tear costs per time unit. Therefore, each engine start and each operating hour causes proportionate costs for maintenance and replacement. For example: A part shall be replaced after 1 000 starts and costs 2 000 €. Hence, this specific engine part adds 2 € per start to the wear and tear costs. At last, the emission costs are directly related to the fuel consumed and the individual costs per consumed emission unit.

Although the battery has high initial costs, it only consumes small and negligible costs during operation. Thus, using the battery costs a proportionate amount of the replacement costs. There are two possible reasons to replace the battery. The battery can reach its maximum lifetime or its maximum number of cycles, i.e. complete discharging. In other words, if we discharge the battery, the remaining number of cycles decreases, and replacement draws closer. However, we always take the ratio between the remaining lifetime and the remaining cycles into account. If a battery were to reach its maximum calendric lifetime one way or another before reaching the maximum number of cycles, further cycles do not generate any additional costs.

The calculation method for the battery costs demonstrates that it is not the goal to determine all cost factors exactly according to reality. Instead, it is necessary to create a meaningful economic comparative measurement through approximations, which can be applied to grid-stable solutions against each other.

Economic optimization is conducted at regular time intervals on the basis of the current status of the overall system. By combining the target functions of grid stability and economic optimization with the various restrictions, the model can generate an economically optimal recommendation for action which implicitly fulfils the criteria of grid stability. The recommended action describes the optimal operation of the individual components for a period of several minutes (e.g., 15 minutes). It is also possible to alter the time window. The multitude of components, input parameters and dependencies lead to high complexity, which is reflected in a high calculation time of several minutes. Since the state of the microgrid can change during the calculation, the result of the economic optimization is checked again after the calculation for compliance with the restrictions of the grid stability. If the calculated solution still turns out to be grid stable, the (business) action recommendation can be implemented. If, however, the solution violates restrictions on grid stability in the meantime, the calculated recommendation for action shall be rejected and the optimization initiated again.

A.4.4 Demonstrator and evaluation

A.4.4.1 Software tool

A.4.4.1.1 Technical platform layout

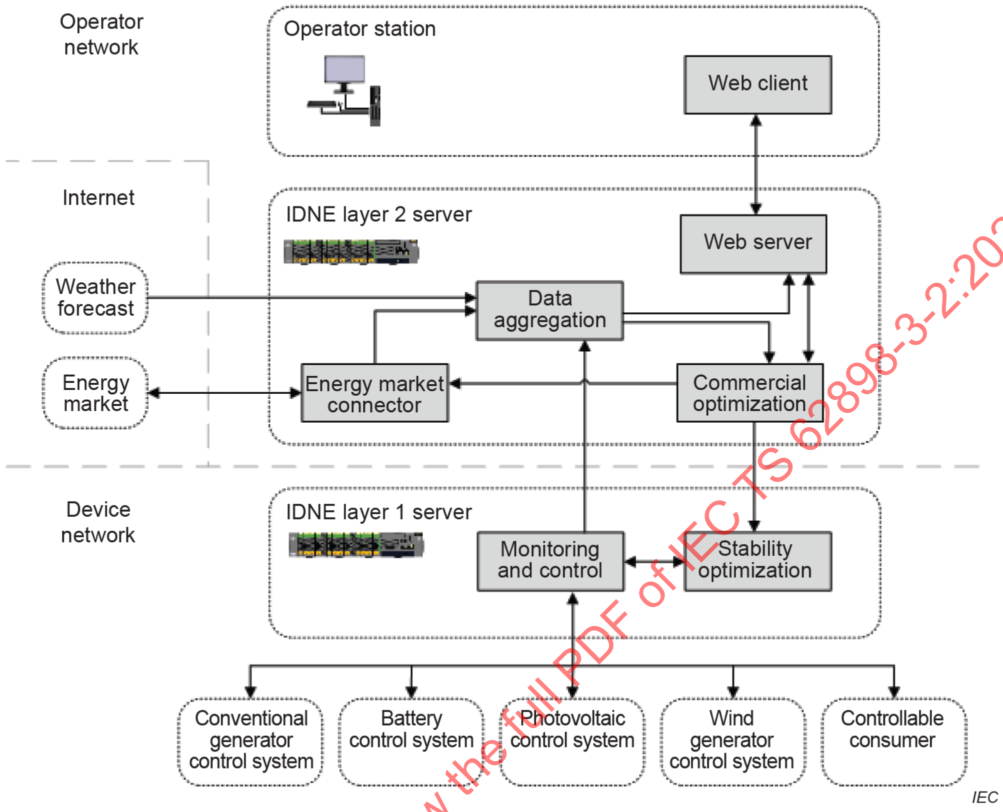


Figure A.8 – Technical platform layout

The system architecture copes with the two-part optimization algorithms and their different aims (stable versus economical solution) by setting up the platform on a two-layer server architecture as shown in Figure A.8. Each layer runs on its own hardware, thus resources for grid stability optimizations are not occupied with some expensive calculation finding economical optimal solutions. Besides, Layer 1 serves as a connector to various power management and consumer systems.

At the lowest level, existing power management systems manage the low-level details of the controlling specific power devices. Typically, these systems have reaction times in the low millisecond range, but are limited to controlling a single logical device. Where possible, these systems are connected to the IDGE platform using standardized protocols mainly based on the IEC 61850 series and secondarily on common industrial communication protocols.

A.4.4.1.2 IDGE layer 1

The IDGE Layer 1 is responsible for maintaining the stability of the microgrid as a whole. Layer 1 server monitors the state of all connected power devices and issues control commands according to the current control strategy. In case of a sudden parameter change that threatens grid stability, such as a surge in power usage, it is the responsibility of this layer to compute and execute commands that re-establish stability before any safety protections are triggered. There are two main components in Layer 1:

- Monitoring and control: This component communicates with the connected control systems. It periodically reads sensor data and sends the current control commands to those devices.

- Stability optimization: A fast-running optimization algorithm that computes a stable grid configuration in real time.

To ensure low response times, IDGE Layer 1 is deployed to a dedicated Linux server that is specifically configured to minimize interruption by background tasks. Furthermore, the IEC 61850 protocol (GOOSE) provides the possibility of real-time functionalities.

Once stable grid operation is established, Layer 2 computes an economically optimized control strategy that coincides with the constraints that ensure grid stability.

A.4.4.1.3 IDGE Layer 2

IDGE platform operations that are not time critical for grid stability are grouped into IDGE Layer 2. This includes the following main components:

- Data aggregation: Sensor data from connected power devices, weather forecast and energy market data is stored and aggregated, both to be sent to the web server for visualization, and as an input for the economic optimization.
- Economic optimization: This component finds an economically optimized stable grid configuration. This optimization can be computed on previously defined time slices or every time there is a significant change to the input parameters or power device capabilities.
- Energy market connector: This component connects to the energy markets and executes trades according to a strategy computed by the economic optimization module.
- Grid operator access: Connection to grid operator for control of active and reactive power as well as failure behaviour.

A.4.4.2 Demonstrator

In order to validate and further develop the software and underlying algorithms, a small microgrid is set up at MAN's premises.

This demonstrator comprises the following hardware components:

- Gas Genset (395 kWe), Cos (phi) 0,2 – 0,8
- Li-Ion Battery Storage, 112 kWh, 2C
- PV-Plant (40 kWP)
- PV-Inverter: STP 20.000 TL-30 (20 kVA)
- Battery-Converter: WS Tech BAT280 (grid-forming and islanding capability)
- Off-Grid Application as first step, but Grid-Connection to the local MAN medium voltage grid.

The above configuration was selected in order to demonstrate and test all scenarios and use-cases.

This demonstrator can operate both in off-grid and on-grid mode. Thus, all relevant scenarios described above can be evaluated.

Based on current evaluations, we identified the following points as most critical for a microgrid control system:

- Stability-control and economical optimization cannot run in one joint model, due to performance issues.
- Hardware for Layer 1 and Layer 2 should be separated to avoid performance delays.
- In order to ensure grid stability, the control shall be local; a "cloud"-approach is not useful due to the fact that many remote areas have weak or no permanent connection.

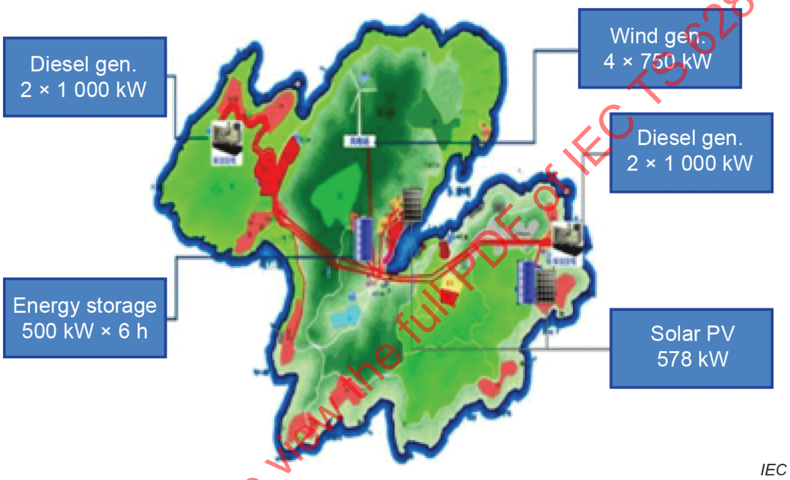
- Redundant check of Layer 2 is necessary to avoid a closed-loop-optimization without checking the stability requirements.
- Physical correlations can be simplified in most cases, without significant loss of accuracy.

A.5 Application CN4: Electrifying islands with wind-PV-diesel-energy storage and hybrid microgrids

A.5.1 Overview

Off the southern coast of Zhuhai in China, Dong'ao Island microgrid and Guishan Island microgrid are two isolated microgrids established by the *Island Microgrid Cluster Project*.

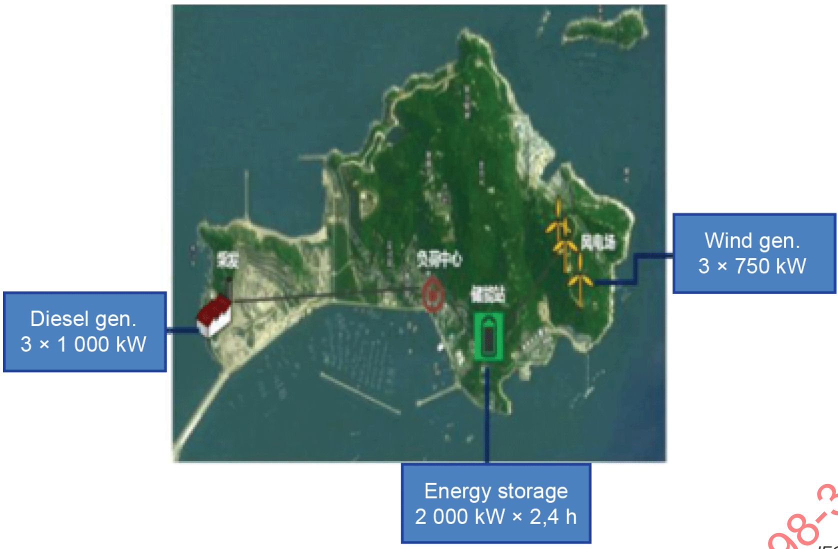
Dong'ao Island microgrid is the first 10 MW level isolated MV microgrid in China. The microgrid contains 4 × 750 kW wind turbine generators, 578,48 kWp solar-PV, 4 × 1 000 kW diesel generators and 500 kW × 6 h lithium batterie based energy storage. Figure A.9 shows the network topology of Dong'ao Island microgrid.



Mr. Xiyuan Ma has kindly provided the above figure.

Figure A.9 – Dong'ao Island microgrid network topology

Guishan Island Microgrid network topology is constituted by 3 × 750 kW wind turbine generators, 3 × 1 000 kW diesel generators and 4 × 500 kW × 2,4 h lead-carbon batterie based energy storage. Figure A.10 shows the network topology of the Guishan Island microgrid.



Mr. Xiyuan Ma has kindly provided the above figure.

Figure A.10 – Guishan Island Microgrid network topology

A.5.2 Purpose

These microgrids are commissioned to improve stability and reliability of power supply on Dong'ao Island and Guishan Island while utilizing renewable energy resources on the islands.

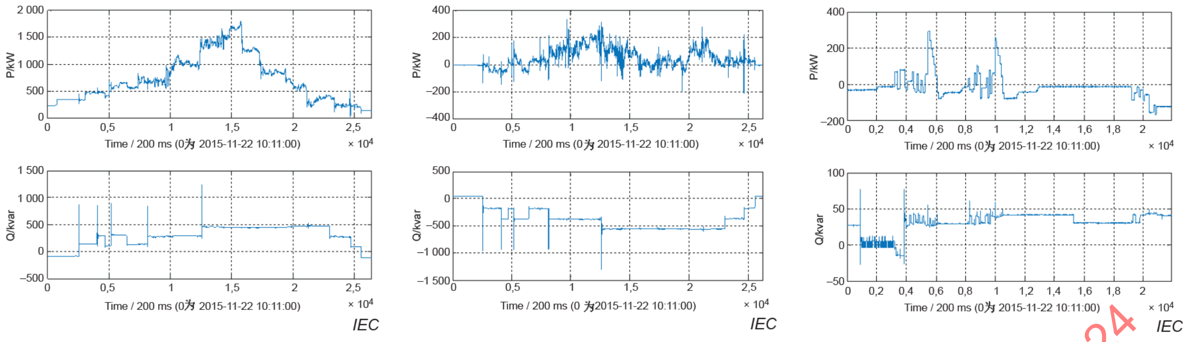
A.5.3 Main functions of MEMS

The main functions of MEMS include seamless switching of main generation source, economic operation, emergency frequency regulation, over-voltage/over-frequency generator tripping, under-voltage/under-frequency load shedding, black-start, etc.

A.5.4 Applications

Under the optimization of MEMS, annual power supply reliability of Dong'ao microgrid reaches 99,79 %. Frequency and voltage deviations are well within the tolerance of relevant national standards. Real-time renewable energy penetration level can be as high as 99 %. Energy storage is capable of participating in frequency regulation with response time of less than 10 ms while acting as a key role in peak load shifting.

EMS of Guishan Island microgrid coordinates power output from diesel generator, wind turbine generator, and energy storage and utilization of renewable energy resources is improved by 32 %. Under low wind conditions, diesel generator can operate in parallel with two wind turbine generators while ensuring generator is operating within an economic operation zone. Energy storage can temporarily operate as main generation source in parallel with the wind turbine generator, thus the microgrid is capable of operating with 100 % renewable energy resource. Moreover, waste heat from diesel generator is utilized to desalinate sea water. Consequently, cost on fuel consumption is reduced by more than 30 % and electricity cost is lowered. Figure A.11 shows a snapshot of active power and reactive power sharing among generation sources and energy storage.



a) **Wind generators** b) **Energy storage** c) **Guishan Island microgrid**

Mr. Xiyuan Ma has kindly provided the above figure.

Figure A.11 – Snapshot of active power and reactive power sharing among diesel generator

A.6 Application CN5: Optimizing local energy resources with demand side integrated microgrid including PV and energy storage

A.6.1 Overview

The demand side microgrid project was carried out through China National High Technology Research and Development Program (namely "863-program"). The project mainly includes four types of microgrids, i.e., community microgrid, residential microgrid, commercial microgrid, industrial microgrid. Details of the four microgrids are as follows (see Table A.2):

Table A.2 – Description of the microgrids

Types	Locations	Configurations
Community microgrid	Village in Yuxi, Yunan Province	60 kW PV, 25,1 kWh energy storage
Residential microgrid	Urban residential area in Guangzhou, Guangdong Province	157 kW PV, 31,7 kWh energy storage
Commercial microgrid	Commercial building of Shenzhen, Guangdong Province	142 kW PV, 90 kWh energy storage
Industrial microgrid	Industrial park in Foshan, Guangdong Province	19,77 MW PV, 900 kWh energy storage

A.6.2 Purpose

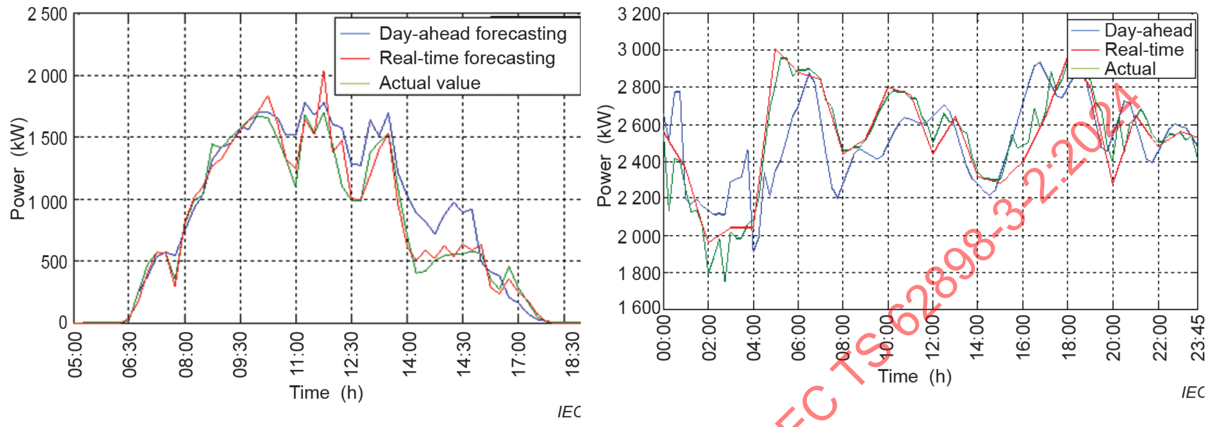
Improve the utilization of solar power resources locally, optimize the economic benefit with the integration of energy storage, and investigate personalized customization of MEMS management strategy for various types of demand-side microgrid.

A.6.3 Main functions of MEMS

Power forecasting, economic optimization, efficiency management, islanding detection, operating mode switching, black-start, etc.

A.6.4 Applications

Power forecasting: solar power forecasting and load forecasting modules are compacted and embedded in the energy management system. The modules supply accurate forecasting results for energy and efficiency management. Figure A.12 shows an actual forecasting example on a particular day in Foshan industrial microgrid.

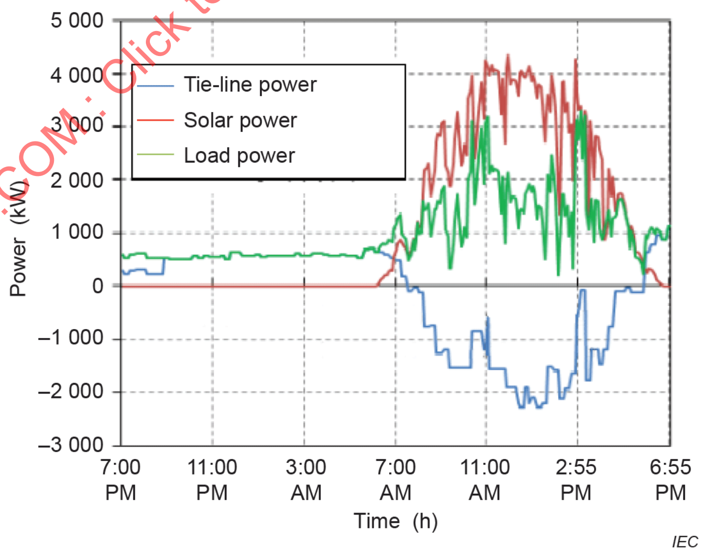


a) **Solar power forecasting performance** b) **Load forecasting**

Mr. Xiyuan Ma has kindly provided the above figure.

Figure A.12 – Solar power and load forecasting in Foshan industrial microgrid

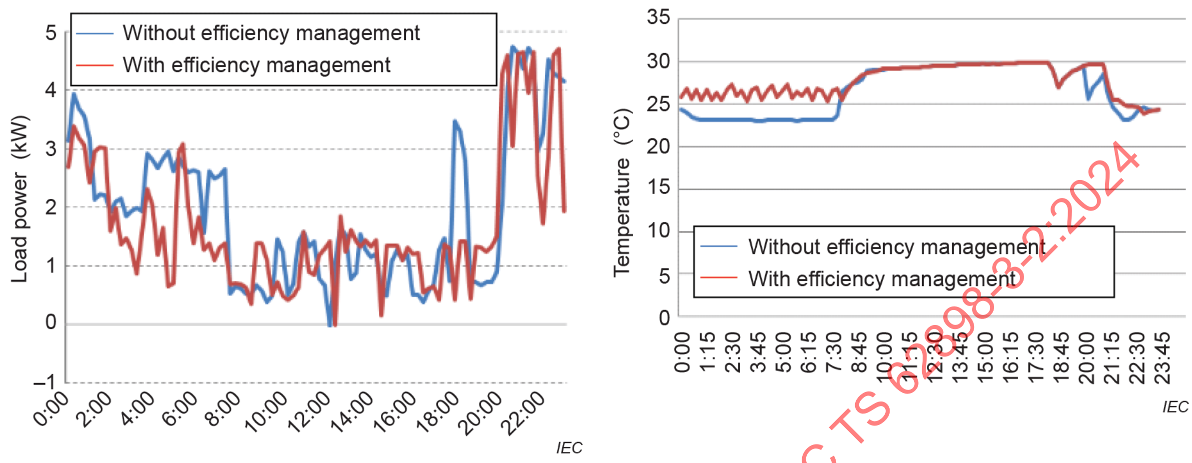
Improving solar power utilization: With the implementation of energy optimization strategy, local solar utilization was significantly improved. Figure A.13 shows power generation and consumption details on a particular day in Foshan industrial microgrid.



Mr. Xiyuan Ma has kindly provided the above figure.

Figure A.13 – Example of power generation and consumption detailed on a particular day in Foshan industrial microgrid

Efficiency management: By manipulating the power of the air conditioner while ensuring the degree of comfort for users, power consumption is reduced, and household energy efficiency is improved. Figure A.14 shows the air conditioner power and ambient/air temperature for a particular user in Guangzhou residential microgrid.



a) **Air conditioner** b) **Temperature**

Mr. Xiyuan Ma has kindly provided the above figure.

Figure A.14 – Air conditioner power consumption and space temperature for a particular user in Guangzhou residential microgrid

A.7 Application JP1: Local independent grid supplied by an energy production system of combining biomass, biogas, wood chip co-firing, photovoltaic and small wind power: the Hachinohe demonstration project from Japan

A.7.1 Overview

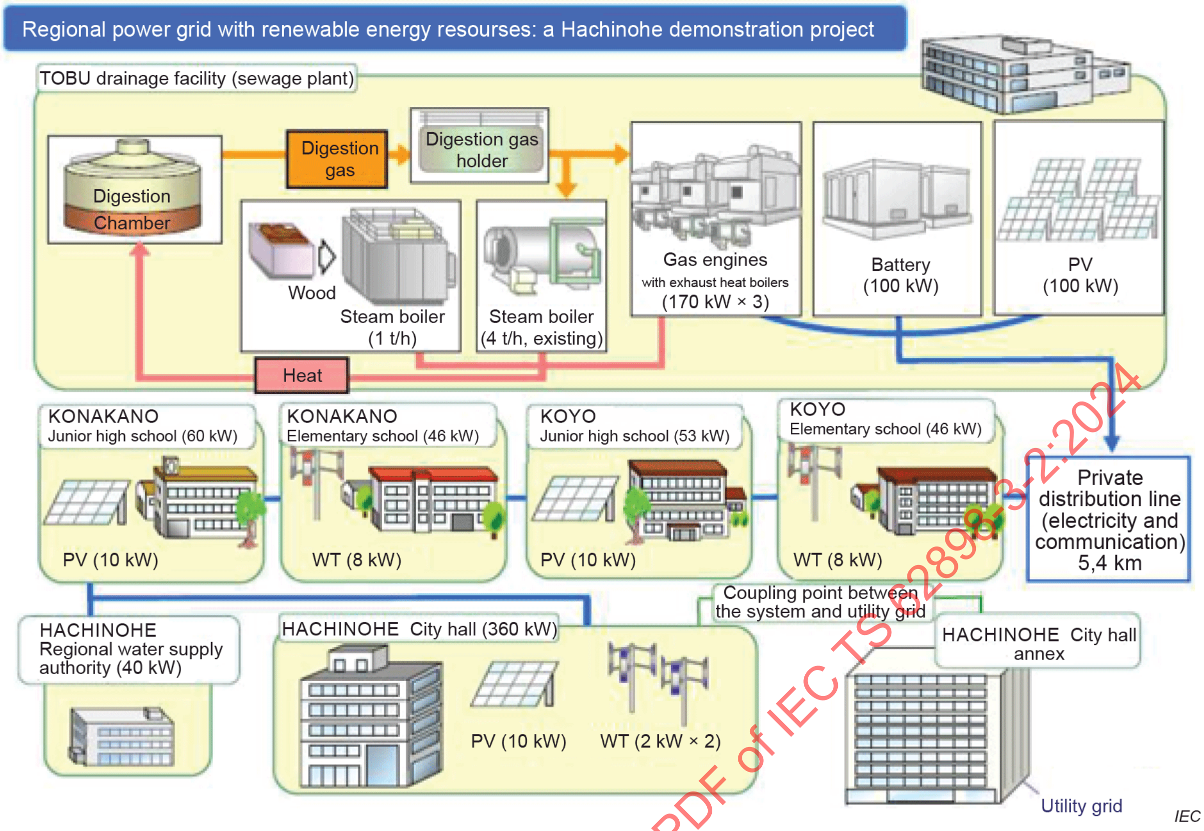
A project demonstrating a microgrid with renewable energy resources has been conducted in Hachinohe, Japan for the period from July 2003 to March 2008.

This demonstration project is a project of the New Energy and Industrial Technology Development Organization (NEDO) in Japan.

Figure A.15 gives an overview of the system. The total capacity of variable renewable generators (PV and WT) is 150 kW, accounting for about 25 % of the total demand of about 610 kW.

As controllable DER, three gas engine generators fuelled by renewable digested gas with a total capacity of 510 kW are also installed.

In addition, a lead-acid battery system, which can generate ±100 kW continuously and −100 kW to +200 kW for short periods, is installed to adapt to sudden demand changes and peak or low demands that cannot be supplied by the gas engines.



Source: P429-436, IEEJ Trans,PE,Vol.128,No.2,2008. NEDO has kindly authorized the use of the above figure.

Figure A.15 – Overview of Hachinohe demonstration project

A.7.2 Purpose

The scope of the project is to develop, operate, and evaluate a dispersed 100 % renewable energy supply system with the ability to adapt the total energy output in response to changes in weather and user demand.

A.7.3 Main functions of the control system

The electricity and heat demand within the system are optimally supplied, controlling the output of the gas engine generators and boilers along with the charge and discharge of the battery system by the project's energy management system. This control system minimizes the operating costs and the environmental burden while maintaining a constant power flow at the microgrid coupling point with the incumbent power utility.

Figure A.16 shows a hierarchical structure of the energy management system, which has four stages as follows.

a) Weekly operation planning is undertaken every day to make a week-long schedule for the operation of the controllable generating facilities and to purchase power from the utility grid based on demand forecasts.

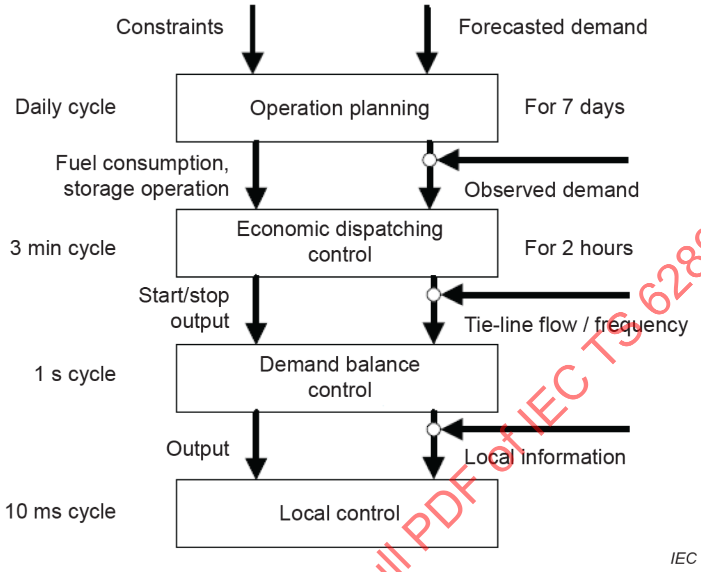
b) Economic dispatching control is executed every three minutes for a time frame of 2 hours to correct the operational schedule based on any difference between the actual demand and the forecasted demand.

   Both a) and b) exploit optimization techniques so that operating costs and environmental burdens are minimized under various constraints. By contrast, the following display the role of power quality control.

c) Demand balance control regulates the power flow through the coupling point at a scheduled value every one second in usual operation. In islanding operation, frequency is controlled with a high degree of accuracy by demand balance control.

d) Local control is used only in the islanding operation, which controls active and reactive power outputs of the battery system every 10 milliseconds to maintain the frequency and voltage within the limits under sudden changes in demand and supply.

NOTE The fast control of 10 ms cycle in item d) is referred to in IEC TS 62898-3-4 as Microgrid monitoring and control systems.

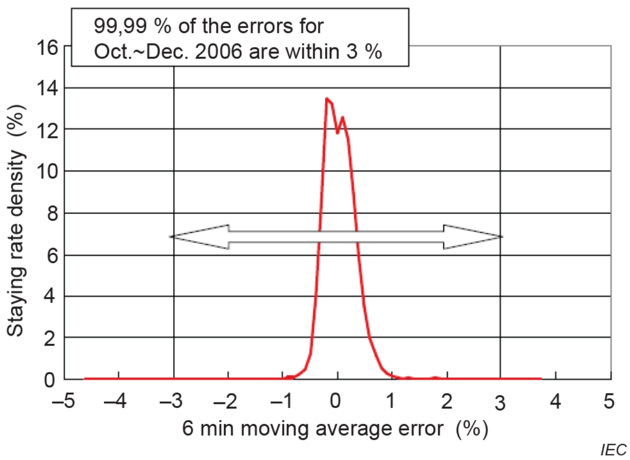


Source: P429-436, IEEJ Trans,PE,Vol.128,No.2,2008. NEDO has kindly authorized the use of the above figure.

Figure A.16 – Hierarchical structure of the energy management system

A.7.4 Applications

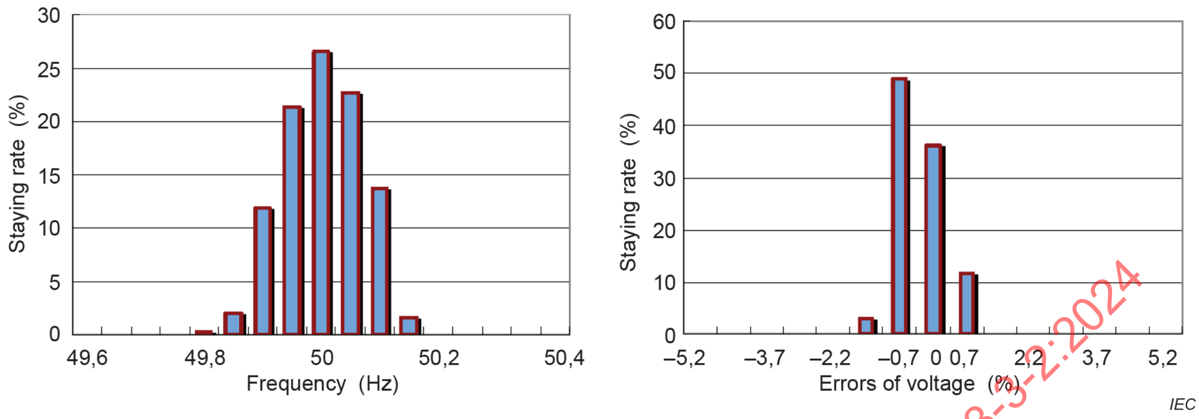
The target value obtained for power flow at the coupling point has a 99,99 % success rate. According to the cycle analysis of the power flow at the coupling point, fluctuations with a cycle longer than 16 seconds have a reduced effectiveness within the control system, see Figure A.17 and Figure A.18.



Source: P429-436, IEEJ Trans,PE,Vol.128,No.2,2008. NEDO has kindly authorized the use of the above figure.

Figure A.17 – Performances for grid connected operation: deviation from planned flow

For the islanding operation, the success rate of maintaining the frequency at 50 Hz ± 0,2 Hz is 99,85 % and that of maintaining the voltage within the rated voltage ± 2 % is 99,99 %.



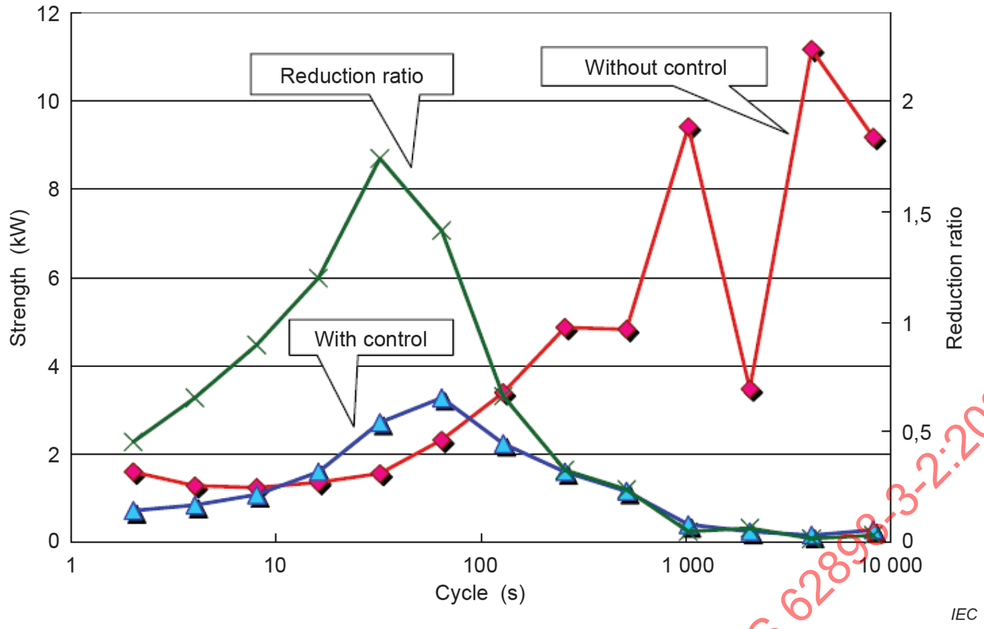
Source: P429-436, IEEJ Trans,PE,Vol.128,No.2,2008. NEDO has kindly authorized the use of the above figure.

Figure A.18 – Obtained success rate of maintaining frequency and voltage

By testing the control system without a battery, it was found there was the possibility for a more economical system operation, as shown in Table A.3 and Figure A.19.

Table A.3 – Description of the microgrids

Case description		**Battery capacity** kWh	**Battery power output** kW	**Success rate of power flow control** %
1) Without limitation	Battery is fully used	400	±100	99,9
2) 50 % limitation capacity	Battery is used as if its capacity was half-sized	200	±100	100,0
3) 50 % limitation of power output	Battery is used as if its power input (inverter) was half-sized	400	±50	99,9
4) No battery use or fixed power output	Basically, no battery is used and only gas engines react to changes. When the demand is too low and is impossible to be supplied by gas engines, the battery activates as a fixed virtual demand	-	Fixed	95,6



Source: P429-436, IEEJ Trans,PE,Vol.128,No.2,2008. NEDO has kindly authorized the use of the above figure.

Figure A.19 – Overall performance under different battery operation modes

A.8 Application JP2: Islanding operation of microgrid with only converter connected resources and no-rotating machine: the 2005 World Exposition, Aichi, from Japan

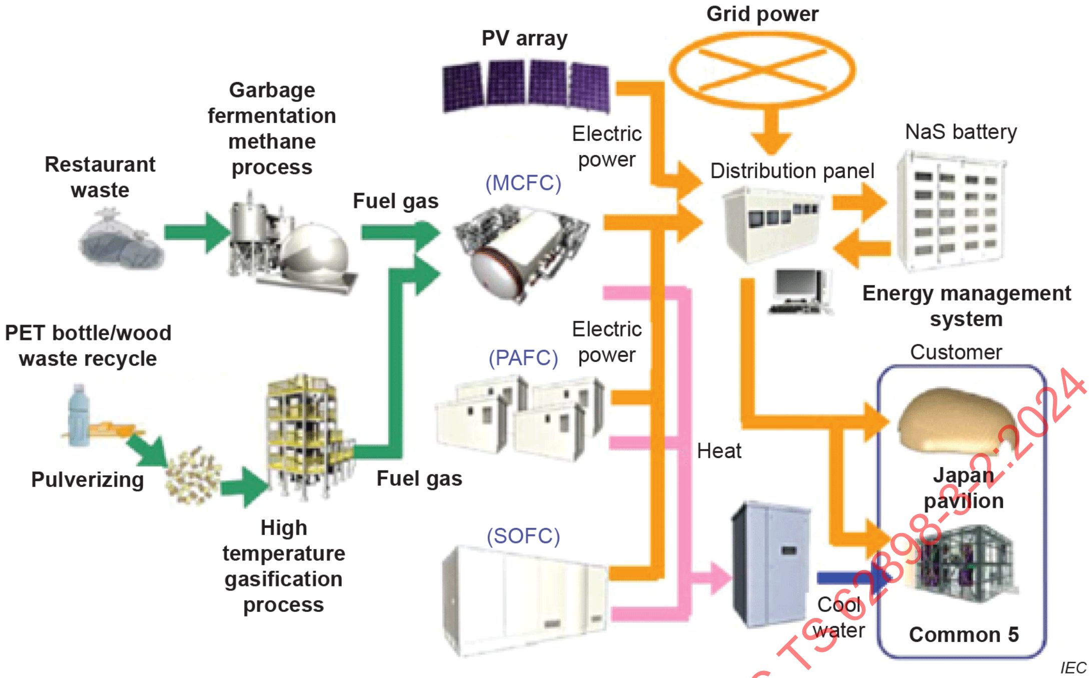
A.8.1 Overview

In this empirical research project, funded by the New Energy and Industrial Technology Development Organization (NEDO) in Japan, cogeneration systems and distributed power sources such as storage batteries are appropriately combined. Each distributed power source is remotely controlled by a central energy management system developed ad-hoc using energy control technology, as shown in Figure A.20 and Figure A.21.

Intentional islanding operation was also performed. During islanding operation, it was proved that it was possible to stabilize and operate the microgrid using only inverter connected resources, in other words without the utilization of rotating synchronized generators.

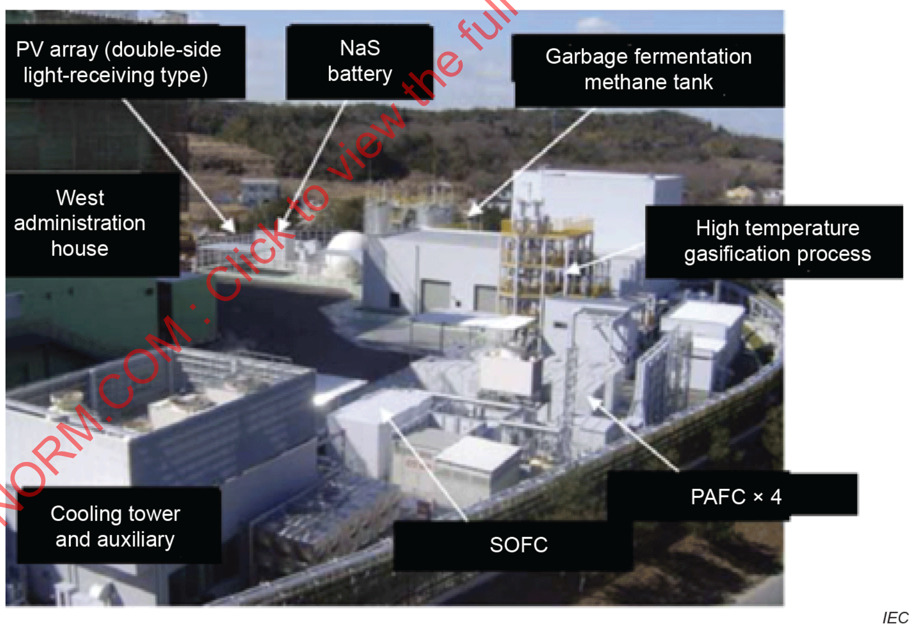
The following equipment was installed:

- hybrid co-generation system with PV,
- molten carbonate fuel cell (MCFC),
- phosphoric acid fuel cell (PAFC),
- solid oxide fuel cell (SOFC),
- NaS battery,
- renewable fuel (methane) production equipment from garbage fermentation and waste plastic/wood chip.



Source: P145-153, Institute of Electrical Engineers of Japan Trans, PE, Vol.127, No1, 2007. NEDO has kindly authorized the use of the above figure.

Figure A.20 – Overview of equipment configuration



Source: P145-153, Institute of Electrical Engineers of Japan Trans, PE, Vol.127, No1, 2007. NEDO has kindly authorized the use of the above figure.

Figure A.21 – Appearance of equipment

A.8.2 Purpose

The scope of the project is to provide a stable supply of power and heat to the demand facilities, and to conduct an empirical study to explore the form of an environmentally friendly microgrid without affecting the commercial power grid.

A.8.3 Main functions of the control system

a) Supply and demand planning function

On the previous day, the power generation amount of the photovoltaic power generation system, the power demand of the demand facility, and the heat demand are estimated from the weather forecast data of the next day and the past measured power demand data. In response to the objectives of "reducing CO_2 emissions" and "improving the overall energy efficiency of power and heat," the power generation plan for renewable energy power generation facilities is optimized on a daily basis (30-minute intervals).

b) Supply and demand control function

The planning function creates the basic plan for the power generation control. However forecasting error for both PV power output and demand consumption have to be processed and integrated with the basic plan to ensure the real time balancing between production and consumption. Three modes for real time control are available based on the microgrid operation status and the contract condition with the interconnected utility:

1) Commercial power fluctuation suppression control

Any deviation of demand or PV production from the forecasted value can create a fluctuation of the power flowing at the interconnection point with the electric utility creating a mismatch between the contracted power and the measured power.

Therefore, the energy management system controls the generation output of NaS battery and fuel cells to correct the difference between the planned value and the actual value in real time.

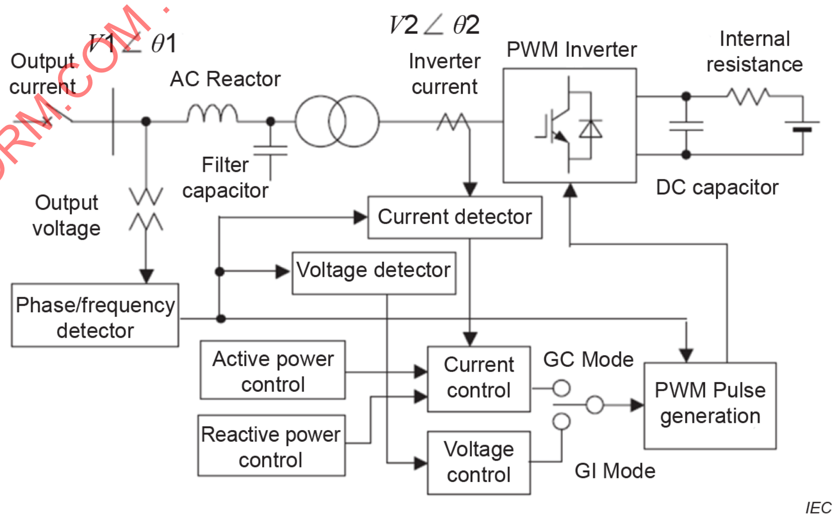
2) Balancing control for 30 minutes

The Japanese electricity market rules include a 30 minutes energy balance rule. In this operating contract mode, the energy management system controls the output generator to ensure that the total energy consumption on the 30 minutes time frame is equal to the total energy production with a maximum deviation of 3 %.

3) Frequency control (islanding mode)

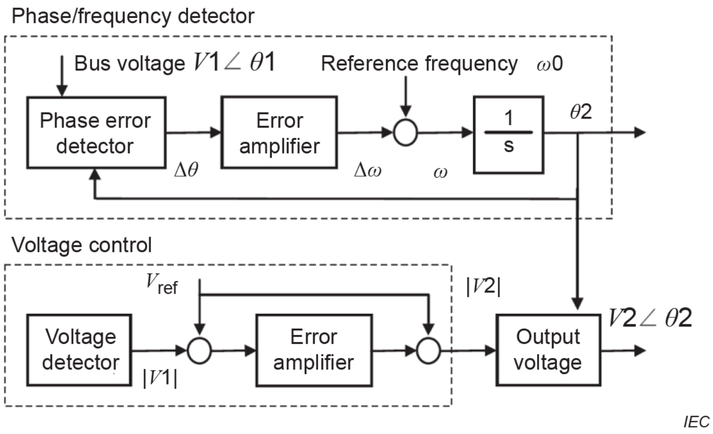
One of the challenges of a microgrid is the control of different types of independent inverters to obtain a stable voltage and frequency in the grid.

In order to solve this problem, it was decided to operate a PAFC that can follow changes in load in voltage control mode and supply/demand adjustment, and operate other inverters at a constant output.



Source: P145-153, Institute of Electrical Engineers of Japan Trans, PE, Vol.127, No1, 2007. NEDO has kindly authorized the use of the above figure.

Figure A.22 – PAFC system configuration



Source: P145-153, Institute of Electrical Engineers of Japan Trans, PE, Vol.127, No1, 2007. NEDO has kindly authorized the use of the above figure.

Figure A.23 – Block diagram for isolated operation

Figure A.22 and Figure A.23 show the main circuit configuration and control circuit of the PAFC. When the microgrid is connected to a commercial system, it is operating in the GC (Grid Connect) mode in the figure, and control is performed according to active power and reactive power given as a command. On the other hand, during islanding operation, it operates in GI (Grid Independent) mode. In this mode, voltage control is selected, and the voltage is determined by the output of the PAFC. In order to reduce the output imbalance due to the control error of the four PAFCs, an appropriate slope characteristic with respect to the output change was given.

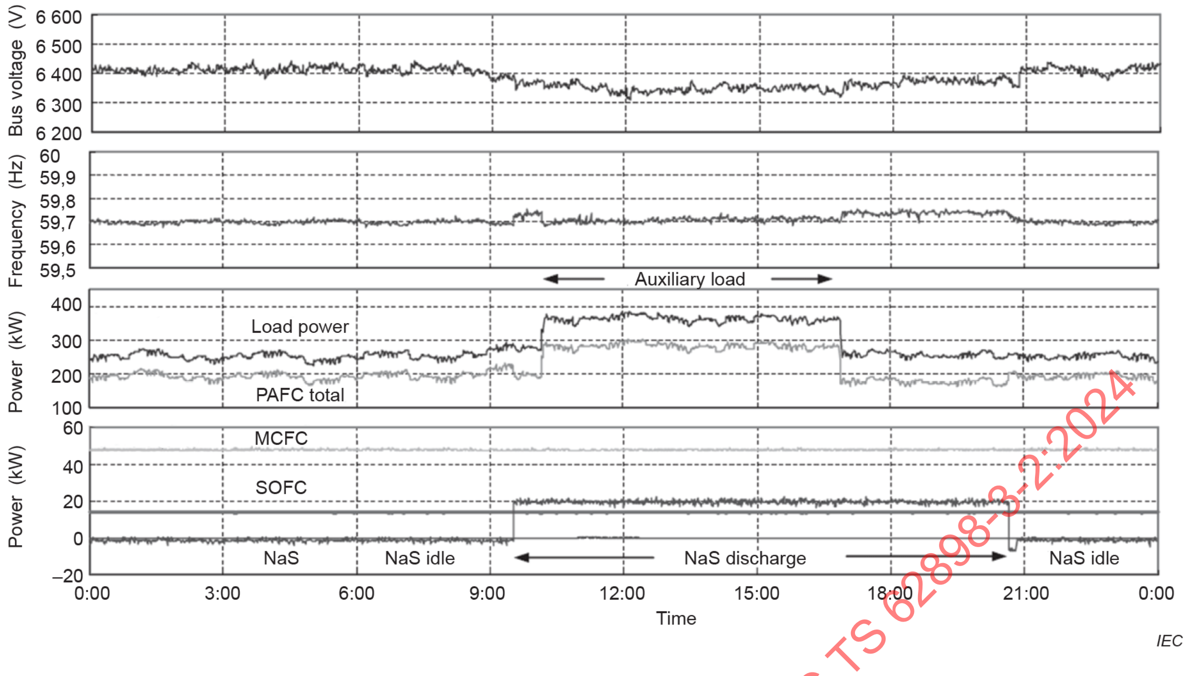
In addition, for frequency, a PLL (phase locked loop) circuit is used. The part that amplifies the phase error of this circuit during islanding operation is set to proportional control, so that when the output increases, the phase error offset remains, resulting in a frequency slope characteristic that increases the deviation.

NOTE For item 3), the topic of stable voltage and frequency operation in islanding mode is referred to in IEC TS 62898-3-4 as Microgrid monitoring and control systems.

A.8.4 Applications

On September 30th, the microgrid was disconnected from the commercial grid, and after a complete de-energization, one PAFC was activated to establish the islanding grid. After that, the second to fourth PAFCs were activated in sequence, and stable operation with 4 PAFCs in parallel was confirmed. NaS battery charging and discharging began on October 1, and SOFC and MCFC started power generation on October 2 and 3, respectively, and all planned power generators were connected.

Figure A.24 shows the voltage and frequency fluctuations throughout the day. The voltage was maintained at about 6,350 V and the frequency was maintained at about 59,7 Hz, and no effect on the power quality on the load was observed.



Source: P145-153, Institute of Electrical Engineers of Japan Trans, PE, Vol.127, No1, 2007. NEDO has kindly authorized the use of the above figure.

Figure A.24 – Power quality (voltage and frequency on Oct. 11th)

A.9 Application JP3: Grasping the impact of mass solar power generation on the actual power system and empirical research on system stabilization measures using storage batteries: Miyakojima Mega Solar Demonstration Research

A.9.1 Overview

During the period from 2009 to March 2016, the impact of a large number of PV installations on power systems was investigated in the remote island power grid on Miyakojima. Under the same project demonstration tests on system stabilization countermeasures such as battery integration, forecasting, resource optimization dispatch were performed and assessed.

This demonstration project was promoted and founded by the Agency for Natural Resources and Energy (ANRE) of the Ministry of Economy, Trade and Industry (METI) in Japan, and was implemented by Okinawa Electric Power Co., Inc.

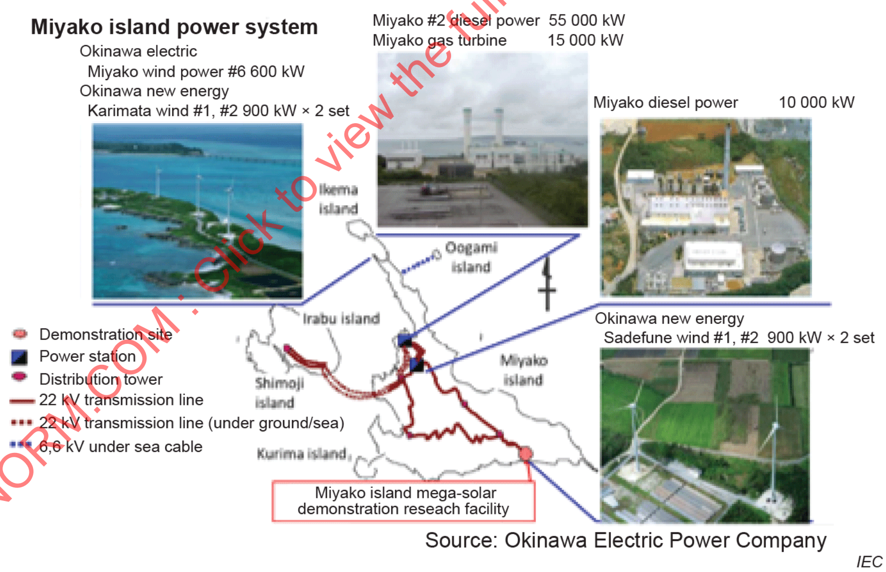
Table A.4 gives an outline of the facility.

Table A.4 – Outline of the facility

Site name	Miyako island mega solar demonstration research facility
Adress	Gusukube, Miyakojima city, Okinawa
Site area	98, 089 m^2
Generation operator	Okinawa Electric Power Co. Inc
Generation capacity	4 MW
Battery storage capacity	4 MW (NaS battery), 100 kW (Li-ion battery)
PV panel type	Multi-crystalline, Amorphous (thin film) solicon
Power conditioner (PCE)	1 MW×3 sets for PV, 500 kW×8 sets for battery and other residential sizes
Load simulator	100-residential load simulator, 4-large load facility simulator
Voltage regulator	Static var compensator (SVC), Step voltage regulator (SVR)

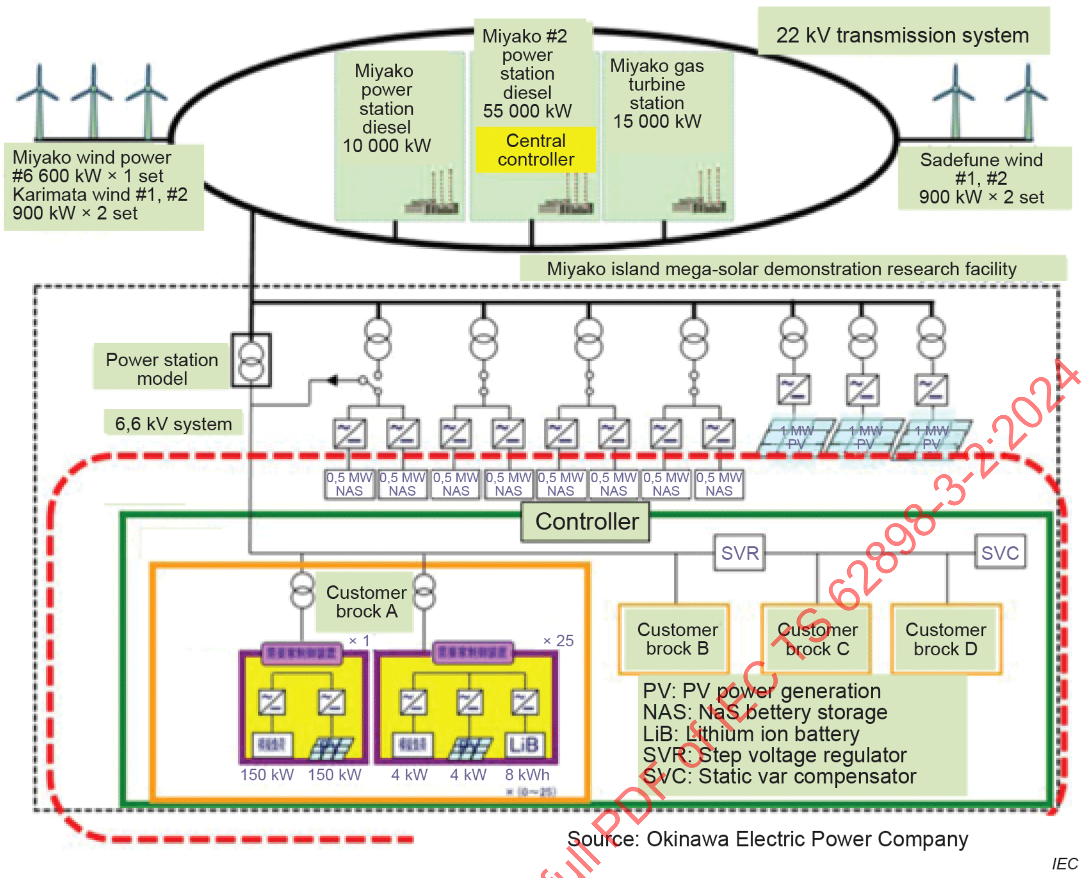
Miyakojima is a remote island with an area of 205 km^2 located 300 km south-west of the main island of Okinawa. There are 23 000 customer contracts and a population of 55 000. The peak demand power is 55 000 kW.

Figure A.25 gives an overview of the Miyakojima island power system. Figure A.26 gives an overview of the demonstration research facility. Figure A.27 gives a picture of the demonstration research facility.



Source: Hybrid/micro grid system with renewable energy in Japan-examples and supposed issues for system certificate, Jun 22,23, 2017, JET (Japan Electrical Safety & Environment Technology Laboratories), Presented at IECRE Task Force meeting: Hybrid/Microgrid System Certification, Date: 22 June (after PV OMC) and 23 June 2017 (am), Venue: Danubius Hotel, Budapest, Hungary1. Mr. Koshio Masanobu has kindly provided the above figure.

Figure A.25 – Overview of the Miyakojima island power system



Source: Hybrid/micro grid system with renewable energy in Japan-examples and supposed issues for system certificate, Jun 22,23, 2017, JET (Japan Electrical Safety & Environment Technology Laboratories), Presented at IECRE Task Force meeting: Hybrid/Microgrid System Certification, Date: 22 June (after PV OMC) and 23 June 2017 (am), Venue: Danubius Hotel, Budapest, Hungary1. Mr. Koshio Masanobu has kindly provided the above figure.

Figure A.26 – Overview of the demonstration research facility

Source: Okinawa Electric Power Company

IEC

Source: Hybrid/micro grid system with renewable energy in Japan-examples and supposed issues for system certificate, Jun 22,23, 2017, JET (Japan Electrical Safety & Environment Technology Laboratories), Presented at IECRE Task Force meeting: Hybrid/Microgrid System Certification, Date: 22 June (after PV OMC) and 23 June 2017 (am), Venue: Danubius Hotel, Budapest, Hungary1. Mr. Koshio Masanobu has kindly provided the above figure.

Figure A.27 – Picture of the demonstration research facility

A.9.2 Purpose

Remote islands rely on diesel generators for most of the power source. This project identified problems caused by the replacement of diesel generators by a large number of renewable sources (such as photovoltaic and wind turbines) due to carbon reduction and introduced technologies solving them. Specifically, the main theme is how to reduce the impact of fluctuations in the output of renewable energy on the grid at low cost by installing storage batteries and EMS (energy management system).

A.9.3 Main functions of the control system

In this demonstration project, the following four functions were verified. In addition, simulation combined with data measurement allowed to design the optimal storage battery capacity necessary for each function.

a) Suppression of output fluctuation (function to suppress output fluctuation of the photovoltaic power generation with storage battery and verification of optimum storage battery capacity). See Note.

b) Suppression of frequency fluctuation (function to suppress frequency fluctuation of the entire system with storage battery and verification of optimum storage battery capacity). See Note.

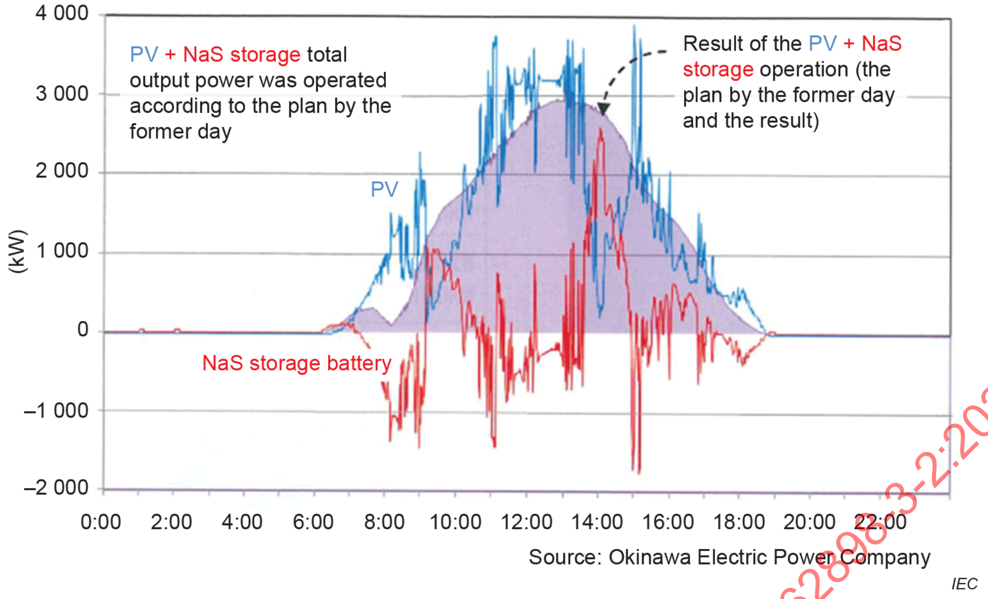
c) Scheduled operation (predicts PV output from meteorological data and obtains an efficient operation method of storage battery and diesel generator).

d) Optimal control method (simulates the power load when distributing electricity to residential loads and commercial facilities with PV and storage batteries connected).

NOTE Suppression functions of output power and frequency fluctuation are referred to in IEC TS 62898-3-4 as Microgrid monitoring and control systems.

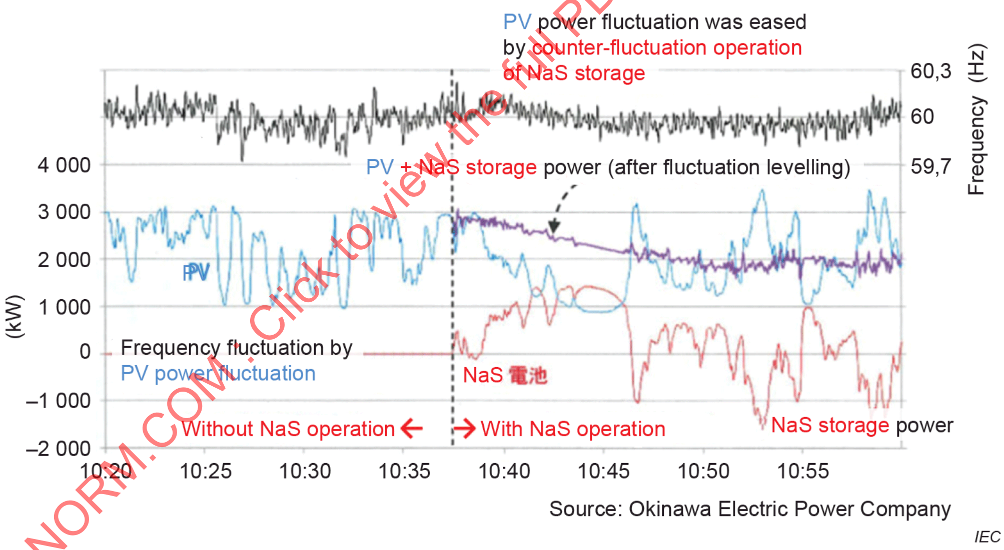
A.9.4 Applications

Figure A.28 and Figure A.29 show the results of NaS battery control for short-term and long-term PV output fluctuations.



Source: Hybrid/micro grid system with renewable energy in Japan-examples and supposed issues for system certificate, Jun 22,23, 2017, JET (Japan Electrical Safety & Environment Technology Laboratories), Presented at IECRE Task Force meeting: Hybrid/Microgrid System Certification, Date: 22 June (after PV OMC) and 23 June 2017 (am), Venue: Danubius Hotel, Budapest, Hungary1. Mr. Koshio Masanobu has kindly provided the above figure.

Figure A.28 – Result of the PV + NaS storage long term operation



Source: Hybrid/micro grid system with renewable energy in Japan-examples and supposed issues for system certificate, Jun 22,23, 2017, JET (Japan Electrical Safety & Environment Technology Laboratories), Presented at IECRE Task Force meeting: Hybrid/Microgrid System Certification, Date: 22 June (after PV OMC) and 23 June 2017 (am), Venue: Danubius Hotel, Budapest, Hungary1. Mr. Koshio Masanobu has kindly provided the above figure.

Figure A.29 – NaS storage operation for short term power fluctuation levelling