A Novel Design for an Expandable, Modular Microgrid Unit

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Abstract—**This paper proposes a modular microgrid unit (MMGU) that can work autonomously but is also capable of connecting to other MMGUs to form an expandable microgrid. Because of various types of resources and power lines, the proposed unit is reliable and robust enough to protect against single failures and generation fluctuation. Storage units are included to enhance the overall performance of the microgrid system by improving reliability, dispatchability, stability, and power quality.**

Index Terms—**Expandability, Microgrid, Reliability.**

I. Introduction

A microgrid is a discrete, distributed generation-based (DG-based) network comprising distributed energy resources and storage units. It is equipped with sophisticated control and automation systems and is able to operate in both grid-connected and islanded modes [1].

Microgrids are flexible and controllable systems that improve the reliability and efficiency of electric service to end users and integrate small-scale power units into the bulk power grid. Microgrids can provide additional benefits to the local utility in the form of dispatchable power for use during peak power conditions and to alleviate or postpone distribution system upgrades [2].

Several microgrid projects are already in service around the world. The Aichi project described in [3] is an independent power system constructed in 2005 in Japan that employs photovoltaic (PV) panels and a battery storage system. The Hachinohe project detailed in [4] features a microgrid system that uses a private distribution line to transmit electricity primarily generated by a gas engine system. Successful implementation of reliable and stable microgrids is an important achievement in recent years.

Although the loads connected to a microgrid continue to grow, the same level of reliability and power quality is expected. This entails expanding the microgrid and providing additional resources. In addition, this requires new studies and new design and commissioning efforts for the entire microgrid. Therefore, expandability is an important factor that must be taken into account when designing a microgrid.

This paper proposes a modular microgrid unit (MMGU) that can work autonomously but is also capable of connecting to other MMGUs to form a larger microgrid. New units can simply be added when the load increases. A real-time automation, control, and protection (RTACP) system provides distributed control and protection logic for each MMGU and can communicate with other MMGUs through an Ethernet network. This paper presents the single-line diagram of the proposed MMGU and lists the key power equipment as well as the typical values of the MMGU elements. Various modes of operation are discussed and possible control and protection strategies are outlined. In addition, the automation scheme for each MMGU and for all of the MMGUs together is discussed in detail.

The MMGU enhances microgrid operation when it is used in conjunction with renewable energy sources (RESs) such as PV units and wind turbines. However, RESs are inherently unreliable and nondispatchable, and they suffer from low stability and poor power quality. The proposed MMGU can alleviate all of the aforementioned drawbacks because it is equipped with dispatchable resources and a storage unit along with intelligent control algorithms.

An MMGU can be applied in any facility that uses a synchronous machine bidirectionally (e.g., to pump and store). Pumped storage power plants, water pump utilities, and offshore facilities are a few applications that can use MMGUs to provide their own power [5].

II. MMGU System Diagram

The system topology and the proximity of generation to loads are two key factors that affect microgrid reliability [2]. In the proposed MMGU, the focus is on developing a reliable unit in which there is minimum distance and interface between the generation and load. Figure 1 shows the single-line diagram of the MMGU and its constituent equipment.

Figure 2 shows the entire microgrid when MMGUs are connected to the main busbar. The main busbar is usually connected to the utility grid at the point of common coupling (PCC). Although Figure 2 shows the incoming single-bus configuration, more reliable arrangements, such as double incoming/double busbar, can be deployed to improve the operation reliability.

A. Components of an MMGU

Some of the key components of an MMGU are described in the following subsections.

1) Synchronous Machine

The synchronous machine is the focal point of the MMGU because it is the only DG in the unit. The machine is operated in both motor and generator modes.

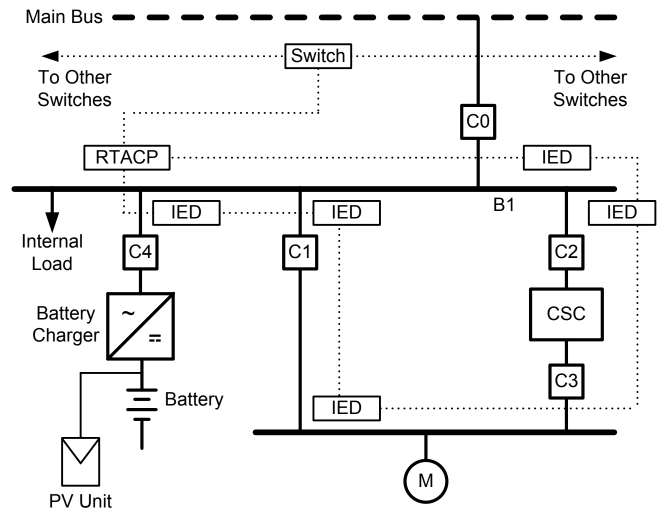

Figure 1. Single-Line Diagram of Proposed MMGU

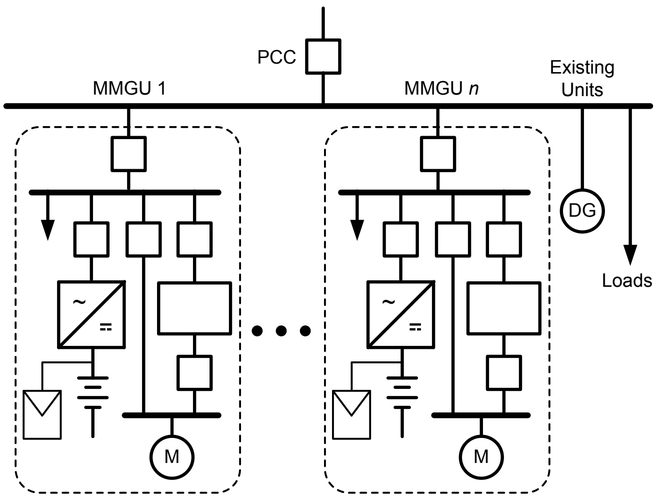

Figure 2. Microgrid Consisting of a Group of MMGUs

2) Variable-Speed Drive

The variable-speed operation of small-scale generation units is a topic of common interest. In the proposed MMGU, variable-speed operation is implemented with a current source converter (CSC) that drives a synchronous machine [5], [6]. Figure 3 shows a CSC circuit comprising a thyristor converter bridge and a thyristor inverter bridge [5], [7].

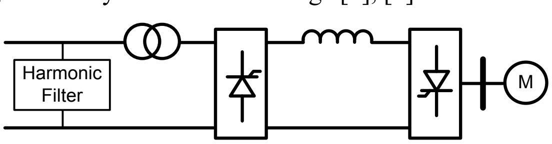

Figure 3. Typical CSC Design

3) Energy Storage Unit

The MMGU storage unit is made up of two connected parts: a battery and a charger. Battery systems store electrical energy in the form of chemical energy. The charger is generally a bidirectional converter that allows energy to be stored in and taken from the batteries.

In addition to reserving energy for future demand, the battery stabilizes and permits DG units to run at a constant and stable output and seamlessly operate as a dispatchable unit [8]. A 1,500 Ah battery can store the energy from the generator to energize a typical 30 kW load for about six hours.

For most remote sites, PV panels on the top of the roof are an available option. The MMGU is engineered to be capable of using PV panels to directly connect to the battery storage unit, as shown in Figure 1.

4) Intelligent Electronic Devices (IEDs)

IEDs have a crucial role in the operation, control, and protection of the MMGU. For each feeder, IEDs are installed that locally control and protect dedicated zones. All IEDs transfer data to the local RTACP unit based on the IEC 61850 protocol.

B. *Typical Values for Equipment*

Each MMGU is typically designed to provide power for 30 kW of local load and 1 MW of external load. The number of units needed for a microgrid is calculated by dividing the total installed load by the nominal capacity of each unit, and that number grows by increasing the installed external load. A more detailed method of finding the minimum number of MMGUs required is a reliability assessment of the entire microgrid based on the total load and acceptable level of reliability indices (e.g., System Average Interruption Frequency Index [SAIFI] and Customer Average Interruption Frequency Index [CAIFI]). Table I lists a typical value for all of the elements in the MMGU.

TABLE I. TYPICAL VALUES FOR MMGU ELEMENTS

MMGU Element	Range	Typical Value
Voltage (kV)	0.48–4.16	0.48
Synchronous machine (MW)	0.5–2	1
Battery (Ah)	1,000–2,500	1,500
Circuit breakers (A)	800–1,200	1,000
Local load (kW)	25–50	30

III. MODES OF OPERATION FOR AN INDIVIDUAL UNIT

The main advantage of the proposed MMGU is the flexibility in different operation modes. Each mode needs a certain combination of breaker statuses, which may be achievable either automatically, through operator initiation, or manually.

Table II shows all of the possible operation modes and statuses of the breakers. In this table, 0, 1, and – stand for open, close, and "do not care" conditions, respectively.

TABLE II. POSSIBLE MODES OF OPERATION

Operation Mode Name	C0	C1	C2	C3	C4
Fixed-speed motor (FSM)	1	1	0	0	–
Variable-speed motor (VSM)	1	0	1	1	0
Variable-speed generator (VSG)	–	0	1	1	–
Battery discharge	–	–	–	–	1
Battery charge	–	0	1	1	1
Volt-ampere reactive (VAR) compensation	1	–	–	–	–

A. FSM Mode

FSM mode represents the simplest mode of operation in that there is no power electronic equipment between the motor and outgoing feeder and the motor is energized through the bulk power system.

B. VSM Mode

Although FSM mode is more affordable and reliable than VSM mode, it has some important drawbacks to consider:

- Vulnerability to undervoltage and underfrequency of the utility bus.
- Voltage stability problems during the VAR deficiency in the system.

VSM mode entails more expensive design and more complicated control, protection, and automation implementation. The design is less reliable in comparison with FSM mode. On the other hand, the power electronic interface provides a higher level of controllability and protection. VSM mode can also be used to start FSM mode in order to limit the starting current [9], [10].

C. VSG Mode

When the synchronous machine is in generation mode, it generates power and sends it to the main bus. In such cases, Breakers C2 and C3 are closed, but Breaker C1 is open.

D. Battery Discharge Mode

When Breaker C4 is closed, the battery starts transferring energy to the grid. Although the main application of the discharge mode is in islanded mode, it can also be used in grid-connected mode, especially during peak load or when PV panels are installed and generate power.

E. Battery Charge Mode

When Breaker C4 is closed while Breakers C1, C2, and C3 are open, the generator starts charging the battery. The installed battery stores the energy when the generator produces more power than the internal demand and the selling price is lower than the generating cost—specifically around midnight.

Battery chargers are not fully efficient because a portion of the input power is dissipated during ac/dc conversion. Thus, it is good practice to not charge the battery through the utility. Instead, the battery can be charged through the PV solar panel units or when the synchronous generator can generate power and the connected load is lower than maximum generation capacity of the synchronous machine.

F. VAR Compensation Mode

In VAR compensation mode, the main responsibility of the synchronous machine is to produce reactive power to maintain the voltage magnitude |V|.

When the microgrid is in grid-connected mode, VAR compensation is the most desirable mode during peak load time. Transferring reactive power to end users is more difficult than transferring active power. Deficiency in transferring reactive power causes excessive voltage drop, approaching the voltage collapse point, and finally separating from the entire network [11]. In this mode, the synchronous machine generates and injects the reactive power into the network.

IV. Real-Time Automation and Control

For the proposed MMGU, special control systems are required, and they are integrated through an automation system.

A. Automation System

In order to provide data communication among the IEDs of an MMGU and among all MMGUs, a fast, fault-tolerant, and reliable automation system is required. The following subsections describe an Ethernet-based communications system with IEC 61850 protocol that meets this requirement.

1) Network Topology

The proposed automation network is an Ethernet network with a ring topology. Each IED has a dual Ethernet port, behaves as an autonomous switch, and connects to the RTACP unit through a fiber-optic loop. The RTACP unit is connected to an Ethernet switch. A fiber-optic mesh among the switches of all of the MMGUs enables data communication and the implementation of interunit control and protection logic. Figure 4 shows the network topology of the automation system.

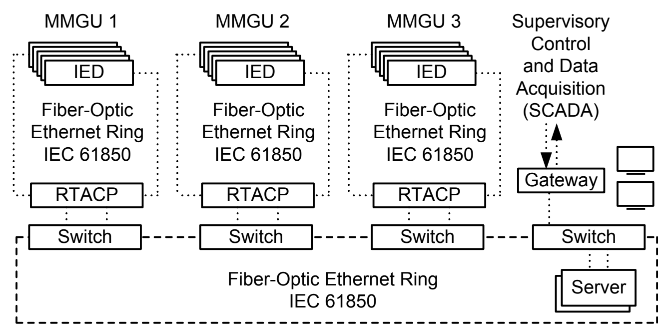

Figure 4. Automation Scheme Diagram

Using a ring topology enhances the network reliability because of the redundant paths to transfer data and tolerate a single failure. However, the intended redundancy needs to be managed in order to avoid circulating the data frames, which leads to increased network traffic and reduces transmission bandwidth. Rapid Spanning Tree Protocol (RSTP) detects loops and breaks them logically inside the switches. In fact, RSTP creates a single, active path between any two nodes within a ring or mesh network of Ethernet switches using the spanning tree algorithm [12].

2) IEC 61850 Protocol

IEC 61850 is the leading communications protocol among IEDs inside an MMGU or between two different MMGUs. The main advantage of IEC 61850 is its interoperability. For example, if the IEDs of a newly added MMGU are from a different manufacturer and IEC 61850 is enabled, the MMGU can successfully communicate with existing MMGUs.

Generic Object-Oriented Substation Event (GOOSE) messaging is the primary method to send and receive statuses, commands, and sampled values. A GOOSE message, defined under the IEC 61850 standard, can be transferred inside an Ethernet network reliably and fast [13].

3) *Station Level and SCADA*

For all units, a centralized station level is prepared in which two redundant servers gather, manipulate, and archive data for further studies. Station-level monitoring and control are available through redundant human-machine interfaces (HMIs). A gateway is provided that bidirectionally connects the units to SCADA.

B. Control System

Control and operation logic are decentralized and implemented in the bay level inside the RTACP unit of each MMGU. The decentralized control in each MMGU allows for small, autonomous systems that communicate with each other. However, decentralized control requires significant experimentation with coordination before implementation [2].

1) *Automatic Controls*

Automatic controls are those that the controller is continuously running or those initiated by the controller, not the operator. The RTACP unit continuously monitors the network, collects data, and sends commands when required. The following subsections discuss the automatic controls required for an MMGU.

a) Scenario 1: Power Freqency and Volt/VAR Control

The power frequency and volt/VAR characteristics of DG units provide the required active and reactive power to adjust the voltage and frequency in the MMGU. The RTACP unit is responsible for maintaining the frequency in a microgrid by tuning the synchronous generator according to its frequency droop characteristics and available storage units. Moreover, the RTACP unit can use voltage control strategies that consider the voltage and reactive power droop of the synchronous generator [1], [2].

b) Scenario 2: Generation Curtailment

If utility regulations, such as Rule 21 in California, prohibit microgrids or individuals with power generation sources from exporting any power to the bulk grid, certain control logic is required.

In order to implement generation curtailment, an under-power (32) function with two levels is used. If the imported power is below Level 1, the RTACP unit closes Breaker C4 to decrease the amount of transferred power to the bus and store it in the battery. If the imported power is below Level 2, or with the closing of Breaker C4 below Level 1, Breakers C2 and C1 are opened to disconnect the generator from the main busbar.

2) *Operator-Initiated Controls*

Some controls are initiated by the operator, and if prerequisites are satisfied, the RTACP unit performs the sequence of operation (breaker switching). The three scenarios described in the following subsections list the sequence of operation of the circuit breakers.

a) Scenario 1: Motor and Generator Mode Switching

The synchronous machine is designed to switch between the motor and generator modes. It is available through a programmable logic controller (PLC) switch, HMI command button, or remote control through the SCADA system.

b) Scenario 2: Machine Soft Start

If the synchronous machine must be started in VSG mode, the following sequence of operation is required: open Breaker C1, close Breaker C2, and close Breaker C3.

In contrast, if the synchronous machine must be started in VSM mode, the following sequence of operation is required: open Breaker C1, close Breaker C0, close Breaker C2, and close Breaker C3.

c) Scenario 3: Motor Source Transfer

It is possible to transfer the motor from one source to another without interruption.

After soft starting the motor in VSM mode, it is possible to switch to FSM mode. In such cases, the following sequence of operation is required: close Breaker C1, open Breaker C2, and open Breaker C3.

For transferring from FSM to VSM mode, the sequence of operation is close Breaker C2, open Breaker C4, close Breaker C3, and open Breaker C1.

The other option is open transition, where the sequence of operation is close Breaker C2, open Breaker C4, open Breaker C1, and close Breaker C3.

d) Scenario 4: Charging the Battery

If the battery needs to be charged, the sequence of operation is close Breaker C3, close Breaker C4, open Breaker C1, and close Breaker C2.

3) *Manual Controls*

The sequential operation of breakers is disabled in manual mode. The operator must open and close the circuit breakers manually, and the task of the RTACP unit is limited to checking the satisfaction of the interlocks as follows to perform the operation:

- Interlock 1—Breakers C1, C2, and C3 cannot be closed simultaneously. In order to close Breaker C1, Breakers C2 and C3 must be open. Also, in order to close Breaker C2 or C3, Breaker C1 must be open.
- Interlock 2—to avoid charging the battery from the utility, Breaker C4 cannot be closed when Breaker C1 is open.

V. Protection System

The MMGU needs various protection functions to protect equipment against all possible faults and during all operation modes.

In modern power system solutions, both control and protection tasks are included in one physical, numeric IED. The MMGU is divided into protection zones as outlined in the following subsections.

A. Motor Protection

The synchronous motor is operated in both FSM and VSM modes. Therefore, two sets of protection that are not identical are required for each. For example, in VSM mode, the synchronous motor can continue its operation even if the network experiences frequency excursion or an undervoltage condition. Thus, underfrequency/overfrequency (81) and undervoltage (27) functions must be disabled when the machine is operating in VSM mode. However, the overvoltage

(59) function cannot be tolerated and must be tripped out to avoid any equipment damage.

B. Generator and Intertie Protection

When the DG is connected to the entire system through an interface, the interface needs additional protection. In the proposed MMGU, when the unit is in VSG mode, the CSC is the intertie. The CSC has its own protection, but instantaneous and time-overcurrent protection must be added to protect the transformer.

In VSG mode, the synchronous machine follows the utility requirements for DG units as described in the example in [14]. Therefore, functions 27, 59, 81U, and 81O of Busbar B1 are imperative.

C. Storage Unit Protection

When the battery is depleted below a certain level, voltage in the battery terminal drops accordingly. Thus, the 27 function automatically opens Breaker C4 to isolate the battery and charger to avoid deep battery discharge and possible permanent battery damage. Likewise, the 59 function protects the battery from overcharging.

D. Circuit Breaker Failure Protection

When a breaker fails to open, adjacent breakers must be tripped out to isolate the fault from the main grid. For example, if the incoming breaker (C0) fails to open during a fault or open command, the C0 breakers in all the other MMGUs will be tripped out. Also, Breakers C1, C2, and C4 must be tripped out.

Circuit breaker failure protection is implemented in the MMGU through IEC 61850 [15]. If a relay senses the fault current or close breaker condition (52A) after the delay elapses, it sends a GOOSE message to subscriber IEDs to trip out their breakers.

VI. Conclusion

This paper proposes the general idea of an MMGU. Some of its key advantages are as follows:

- Expandability—the microgrid is easily expandable by adding new MMGUs to serve more loads.
- Modularity—each unit is analogous to a single brick in the larger structure of the microgrid. Each MMGU has its own control, protection, and automation unit and is able to independently operate.
- High reliability—due to various types of resources and power lines, the proposed MMGU exhibits high reliability and robustness against failures.
- Enhanced power quality and stability—the distributed control algorithm and installed battery unit improve the stability of each MMGU and the entire network.
- Awareness, intelligence, and agility—the RTACP unit provides situational awareness of the entire microgrid and agile control of the system.
- Dual-application synchronous machine—the synchronous machine can be operated in both motor and generator modes, which increases the machine usability and makes the MMGU design more economical and affordable.

The standard design of the proposed unit empowers manufacturers to provide a complete unit (including all equipment, automation, control, and protection devices and protection and control function settings) in a single package, minimizing the design, calculation, and testing time and efforts. Potential applications of this unit are in pumped-storage power plants, water pump utilities, and offshore facilities [5], [16].

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