Model-Driven Microgrid Design, Validation, Controller using ETAP Software

Abstract

ETAP microgrid controller is founded based on a model-driven approach, digital twin technology, and dedicated software development framework that is a combination with ETAP software that significantly simplifies the development and testing of microgrid control functions as well as performing microgrid design and control studies. This controller offers various built-in functions such as Optimal Dispatch, Planned Islanding, Unplanned Islanding, Islanding Operation, Black Start, Reconnect, Renewable Smoothing, and Reactive Power Control to manage microgrid in both grid-connected and islanded modes as well as facilitating seamless transition between both modes.

Introduction

A microgrid is a cluster of interconnected Distributed Generations (DGs), loads, and Energy Storage Systems (ESSs) that can operate in grid-connected and islanded modes. Compared to a single DG, the microgrid can provide more significant technical advantages, control flexibilities, economical operation, and better means of improving energy efficiency. Dispatchable resources, especially energy storage systems, are vital assets to enable microgrid operation in islanded mode. Besides, energy storage systems can maximize and facilitate seamless integration of renewable energy resources by controlling the microgrid import/export power at the point of interconnection (POI). This allows microgrids to be more like conventional loads from the electric grid perspective.

To manage and control microgrid dispatchable assets in both grid-connected and islanded modes and transition between these two operation modes, a microgrid control system is required to determine dispatchable quantities based on various possible objectives constraints. A microgrid control system can be implemented in a centralized or distributed manner. In a typical configuration, the microgrid control system is realized by a microgrid controller that is located close to the microgrid POI. This controller communicates with local controllers that directly or indirectly control microgrid dispatchable assets as well as POI IEDs or circuit breakers and other IEDs, switches, or breakers within the microgrid.

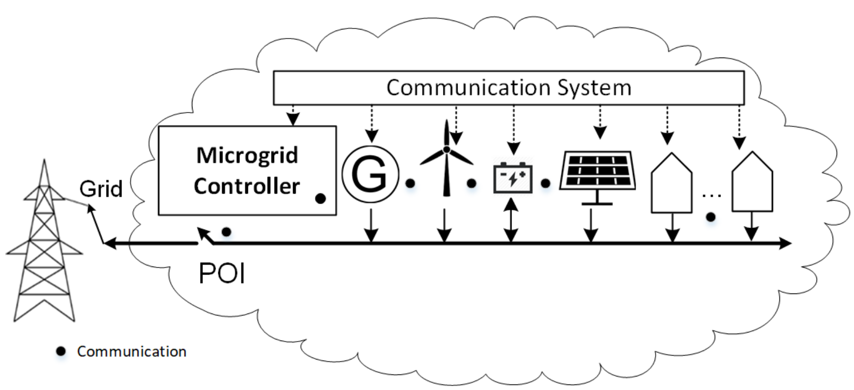

Figure 1 Microgrid System

As per IEEE 2030.7, the microgrid control system has three levels of control functions.

- Level 1 - implemented at the DER/Load/Device level (lower-level)
- Level 2 - required at the microgrid/POI level to facilitate the transition between grid-connected and islanded modes of operation and simple rules to dispatch microgrid.
- Level 3 - higher-level functions that perform supervisory control.

A microgrid controller can provide Level 2 control functions and Level 3 supervisory control functions, such as optimal dispatch.

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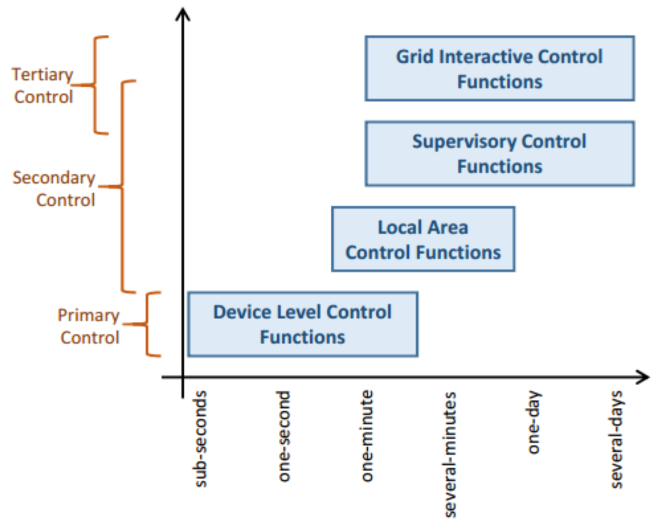

Figure 2 Microgrid Controller Function Levels

Conventional Implementations – Drawbacks & Limitations

Microgrid control strategy and associated control function heavily depend on the type of microgrid and its assets, ratings/sizes, operation conventions, and reliability requirements. One approach is to program an appliance-based controller such as a powerful programmable logic controller (PLC) to meet microgrid requirements. This approach offers flexibility to achieve specific control functionalities; however, it has several limitations as the programmability of a PLC is limited to a certain extent. Besides, this approach requires extensive expert engineering effort to develop/enhance and test new/formerly developed control functions for each microgrid project. This approach limits microgrid controller functions to superficial Level 2 control functions and may not be suitable to implement Level 3 functions such as optimization-based economic dispatch. Besides, handling vast interactions with higher-level supervisory control systems such as ADMS becomes very difficult to implement.

Another approach is to develop a generic microgrid controller with pre-defined functions. Typically, microgrid sources, loads, and energy storage within this type of microgrid controller are user-defined. In this approach, the type of DER constraints and the overall control objectives are part of pre-defined functions. This approach's main drawback is that any new requirement or function that is not supported by the existing control functions may not be achievable without additional product development. For instance, if a microgrid controller does not support controllable loads or curtailable renewables or a microgrid controller does not support nested microgrids, supporting such functions requires enhancing controller logic/firmware and software. Furthermore, a generic microgrid controller becomes suboptimal to accommodate all possible functional requirements. For instance, if microgrid controller economic dispatch is devised based on mixed-integer linear programming (MILP) to accommodate permanently islanded microgrids with multiple types of diesel engines, it will not be sufficient enough for the case of a grid-connected microgrid with battery, curtailable renewables, and dispatchable loads with no diesel engine in operation during microgrid grid-connected mode.

The feasibility study stage of any microgrid project is required to determine the optimal size of renewable energy resources and energy storage systems. Economic dispatch function, along with the employed forecasting algorithm within the microgrid controller, plays a significant role in determining the microgrid's economic benefits. In the case of a generic microgrid controller, typically, the microgrid controller model is not available within a power system simulation and analysis software. Hence, it is impossible to correctly perform a feasibility study unless the microgrid controller vendor does it. In the case of programming a controller to realize a microgrid controller, details of the expected microgrid control functions should be known in advance at the feasibility study stage. This is very improbable. The selected power system analysis tool also needs to have the capability to model and simulate microgrid control logic within time-domain analyses.

Several other limitations and drawbacks of both approaches above elaborated further in the following sections contrast with the ETAP microgrid control system founded based on a Model-driven approach, Digital Twin technology, and novel patent-pending Software Framework for Power System Applications. The next section introduces the ETAP new concept of realizing a microgrid controller that addresses the challenges mentioned earlier.

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ETAP Microgrid Controller Foundation

Model-Driven

Any microgrid controller needs to be aware of its assets, such as energy sources and loads within the microgrid. Conventional microgrid controllers have too many settings to define microgrid, capture various device ratings, operational constraints, and control objectives. This makes it very difficult to work with them. ETAP microgrid solution employs a microgrid model developed in ETAP software during the design phase to receive most of the information required and electrical and communication connectivity. It is important to note that microgrid information entered in the model is stored in a microgrid controller setting file and transferred to the microgrid controller. Hence, the microgrid controller operation is entirely independent of ETAP simulation software. Indeed, new assets can be added or removed, or settings can be changed later by generating and uploading a new setting file to the controller through a HTTPS (web)-based interface. Microgrid controller settings can also be directly changed through the same https-based interface.

In large microgrids where it is possible to create nested microgrids, there will be a POI per each nested microgrid. Microgrid controller needs to know the assets and connectivity within each nested microgrid and main microgrid to manage the primary and nested microgrid simultaneously. ETAP model-driven solution is critical to realize such features as the entire microgrid connectivity, and asset properties are known to microgrid controller.

In distribution system microgrids where a distribution feeder is a microgrid, it is common in case of a fault incident to isolate and restore part of an outage area using neighboring feeders or microgrids. This means that part of one microgrid will be dynamically removed and added to another microgrid. Handling such a feature can be effectively done using the ETAP model-driven approach as the model of the microgrid, and its neighboring microgrids is easily accessible.

Digital Twin

Microgrid controller functionality, implementation, and settings significantly impact the practical and economical utilization of energy resources within the microgrid. It is significantly beneficial to access the model or digital twin of the selected/expected microgrid controller(s) to determine the proper size of renewable energy resources, energy storage ratings, and capacity at the feasibility stage. The ETAP microgrid controller is designed to handle virtualized objects/functions. This means that built-in objects/functions are hardware-independent, assuming that enough processing power and memory are available. Each object/function is defined by input, output, and settings. These objects/functions are cross-platform, i.e., supported in Linux and Windows, and can be executed online within the controller software and offline in the ETAP simulation environment. To also realize such functionality, time is also virtual and consumed within virtualized objects/functions. This technology, as it is obvious, is the enabler of digital twin by nature.

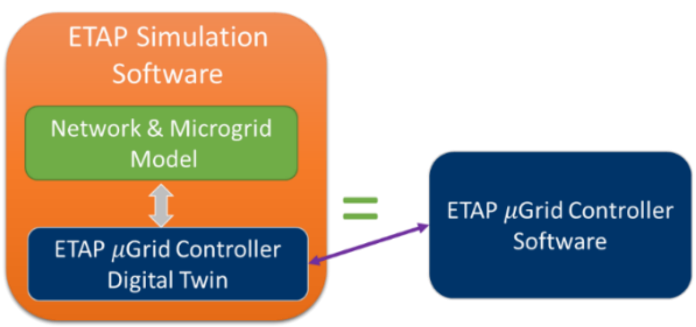

Figure 3 ETAP Microgrid Controller Digital Twin

The ETAP microgrid controller functions can be evaluated in an ETAP simulation environment using a digital twin of the ETAP microgrid controller. ETAP microgrid controller digital twin uses the identical code used in the actual controller. The digital twin of the microgrid controller is represented by a controller element in ETAP simulation software. The controller element is supported within time-domain load flow and transient stability analysis handling all sequence components (positive, negative and zero) and evaluation of all protective devices. Another advantage of using an ETAP simulation environment is that higher supervisory controllers such as ADMS, GMS, DERMS, local DER controllers as well as all protective devices can also be modeled in ETAP simulation software where the interaction of ETAP microgrid controller and rest of the system can be evaluated and demonstrated. Figure 4 shows a sample microgrid and its microgrid controller digital twin and ADMS simulated in ETAP.

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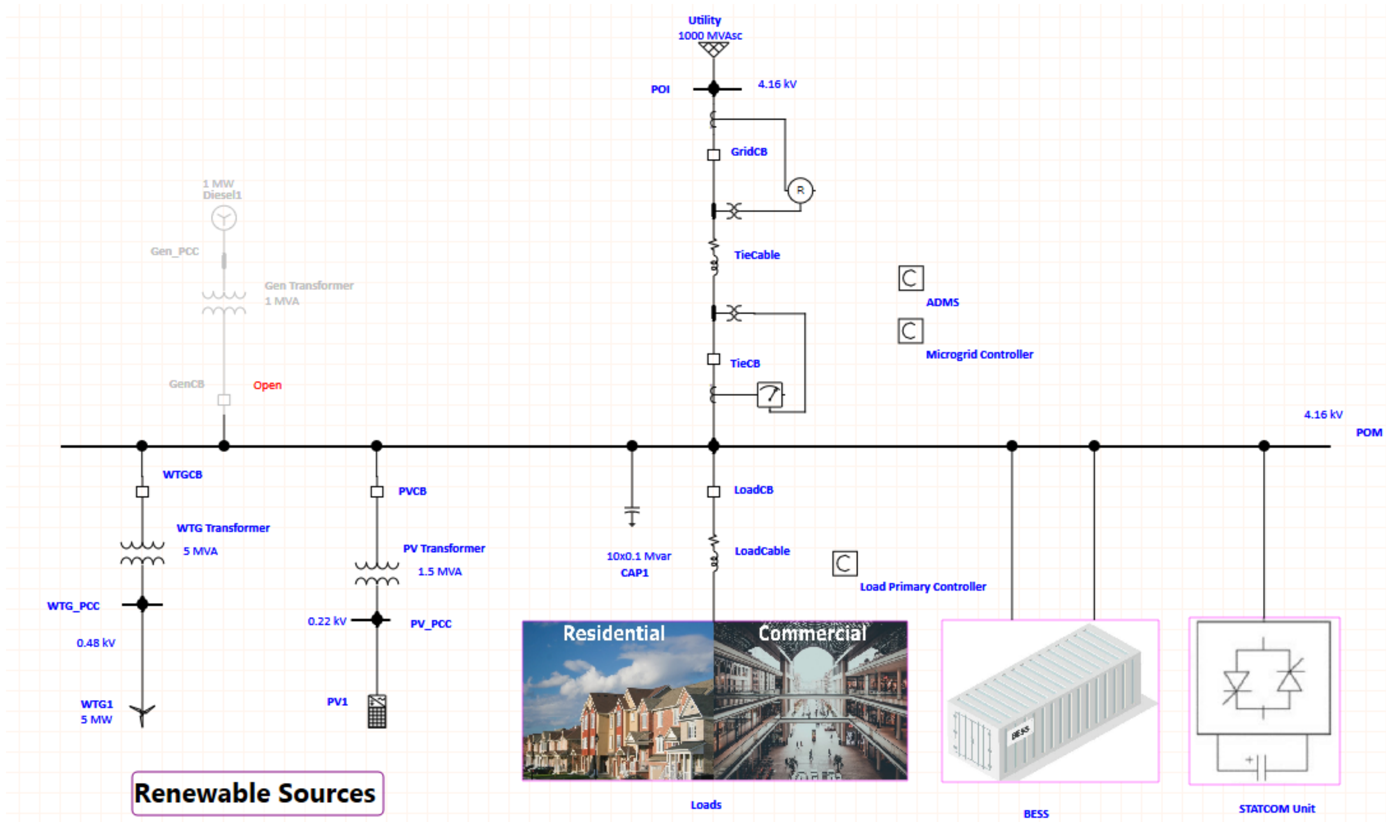

Figure 4 Schematic diagram of the case study microgrid system

Software Framework for Power System Application

Developing new or enhancing microgrid control functions is typically very costly and time-consuming. ETAP microgrid controller software foundation is based on an ETAP patent-pending technology where developing new or enhancing existing control functions is fast and efficient. This feature indirectly benefits customers by enabling ETAP to enhance or develop new microgrid control functions based on customers' requirements in a reasonable and short time fashion. This technology is analogous to developing applications for smartphones in the sense that even a third party can quickly develop, test, and debug applications on this platform in a virtual software environment.

ETAP Microgrid Simulator

A microgrid controller is a supervisory controller that runs every few seconds and utilizes TCP/IP–based communication to monitor and control microgrid. Active and reactive power control functions within the microgrid controller show their response in seconds and minutes. Optimization-based functions typically show their performance in hours or days. The use of conventional real-time digital simulators for testing such functions is expensive and time-consuming. ETAP simulation software offers real-time power flow and transient stability simulation at a microgrid scale (RTMS) while the microgrid controller is in the loop. In this setup, ETAP software runs in a PC simulating a microgrid by performing load flow or transient stability analysis in real-time and transmits all the Microgrid Controller monitoring data through communication to the microgrid controller sending back dispatch commands to ETAP RTMS. In real-time load flow analysis, simulation is performed every one or a few seconds, and at each run, monitoring and control data is communicated with a microgrid controller. In real-time transient stability simulation, the microgrid is simulated every one or a few milliseconds while the monitoring and control data is communicated with the microgrid controller every one or a few seconds. In this real-time simulation, all primary control functions shall be modeled within ETAP simulation software, while microgrid controller supervisory functions are executed within the controller hardware.

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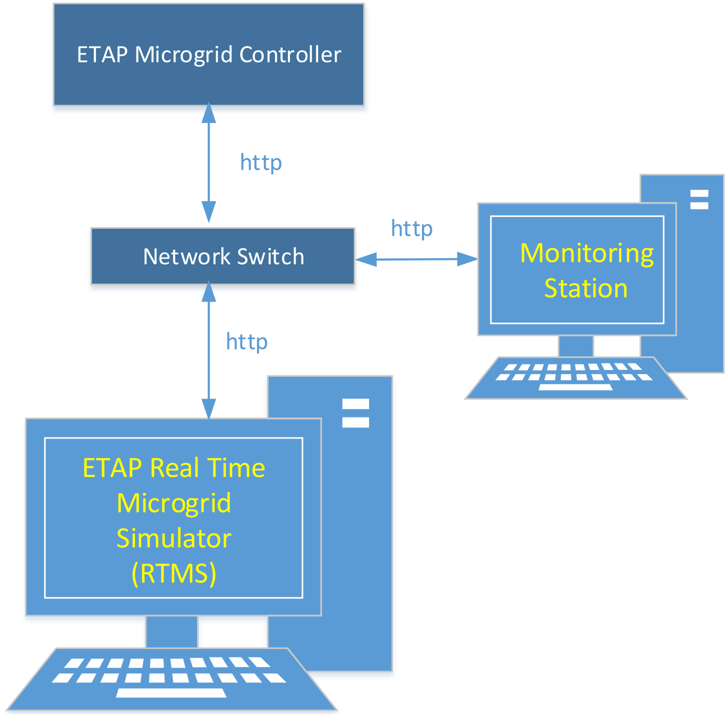

Figure 5 HIL test of Microgrid Controller using ETAP

OVERALL SOLUTION

ETAP microgrid control solution mainly includes an ETAP microgrid controller and a Gateway with high-speed real-time control. In this solution, the ETAP microgrid controller is responsible for performing supervisory control and devising intelligent load shedding (ILS) scheme. Gateway is primarily responsible for converting protocols as needed and provide firewalls if needed for required network traffics. The Gateway's real-time control capability allows us to continuously receive an ILS scheme from the microgrid controller and be ready to act upon detection of unplanned islanding immediately. To implement seamless unplanned islanding, it is critical to detect and communicate either status or trip signal of POI breaker to the Gateway RT controller to initiate ILS scheme. One option is to have a GOOSE message transferred from POI relay to Gateway if possible; otherwise, relay contact outputs can be transmitted through a hardwire to ETAP ICE RTU to generate a GOOSE message informing Gateway RT controller regarding the trip signal or breaker status. ETAP ILS technology has been well established and installed in many sites for more than a decade to provide high-speed load shedding for industrial and microgrid applications with response time under 20 ms.

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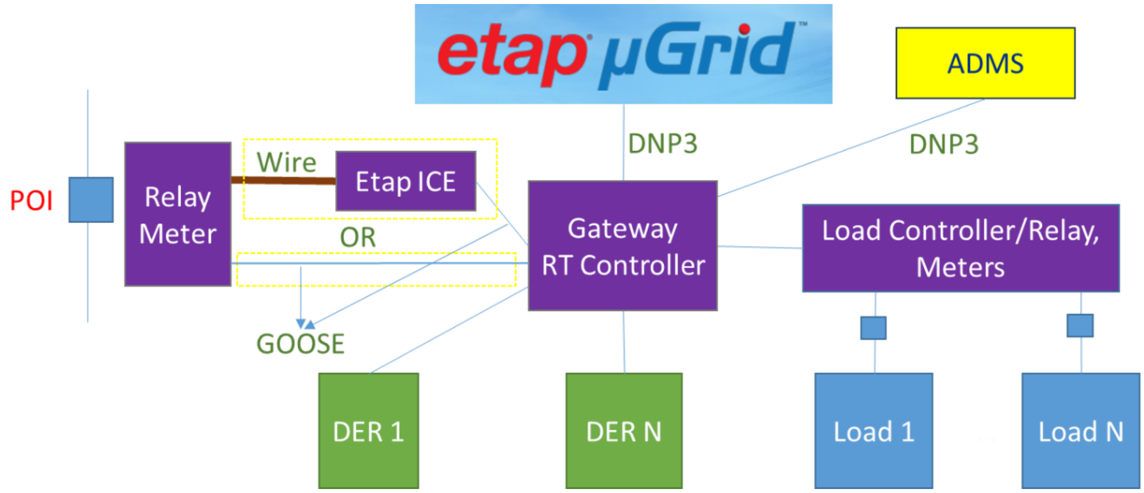

Figure 6 Overall Solution Block Diagram

ETAP Microgrid Controller Functions

In this section, an overview of the ETAP microgrid controller available functions is provided.

Active Power Control

This function controls the active power exchanged at the point of interconnection based on the user's constraints, such as limiting the export power or maintaining a minimum energy storage system (ESS) state of charge (SoC) for unplanned islanding.

Optimal Dispatch

ETAP microgrid controller utilizes demand and generation forecasts and DER and load availability to dispatch DERs and controllable loads optimally. The optimization objectives are 1) minimizing the cost of operation, 2) maximizing the duration of potential islanding, 3) minimizing the amount of load shedding for unplanned islanding, and 4) minimizing the emission.

One of the critical constraints of the microgrid control system (MCS) is to limit/control active power exchange at the microgrid point of interconnection (POI). Power export from a microgrid that is not consumed by nearby loads in the system can exceed the network protectors' reverse-power pickup point and, in turn, can create an unintended island condition for the microgrid system. This function can be defined for each nested microgrid and its associated POI.

ETAP active power control function can dispatch sources to track a particular active power exchange at the POI. MCS dispatches the generating units to track a steady stream of power at POI. If ADMS changes the reference value at any moment, MCS follows the new setpoint by the ADMS.

In case an optimization problem is not solved and end up for an error, preconfigured attempts are made to rerun the optimization. This case will also be reported to ADMS.

This function supports the ability to be configured (via UI and Remotely) to dispatch according to a recurring schedule due to known constraints (e.g., Dispatch BESS to go to xx setpoint every weeknight at 6p for xxx time). Before the scheduled dispatch occurs, an optimization will run to ensure this scheduled dispatch is feasible with the current mode of operation. If not feasible, a log entry and alarm will be created, and the dispatch event will be canceled.

An example is presented here to demonstrate the performance of the Economic Dispatch function for a grid-connected microgrid mode of operation. In this mode, BESS1 and BESS2 are used to zero out power export to the grid and minimize the cost of importing power from the grid. In this scheme, a 24-hour prediction horizon is used as part of the optimization problem. The power of each element in the microgrid is depicted in Figure 7, where BESSs are controlled in an optimal scheme for 24 hours. According to Figure 7, BESSs start charging when the generation exceeds the power demand in the microgrid within 1:00 – 7:00. Next, the BESSs are discharged during the peak of demand to mitigate the grid's imported power.

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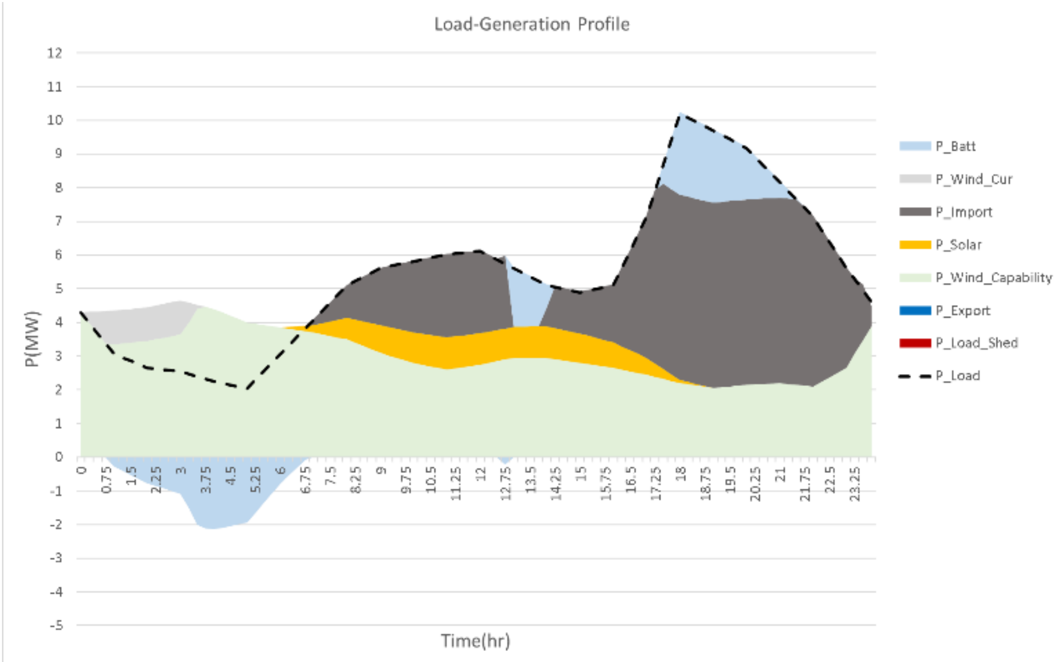

Figure 7 Example of Economic Dispatch function

Renewable Smoothing

In the presence of renewable sources with intermittent output power, if enabled, the ETAP controller utilizes BESS to control and limit the rate at which active power is exchanged at POI. Available BESS's participating in the Renewable Smoothing function can be selected through controller settings. The desired rate limit is also a setting. There is a coordination between the renewable smoothing function and the rest of the active power control functions to ensure that energy storage capacity is utilized adequately by renewable smoothing and other functions.

In an example shown below, BESS1 and BESS2 are utilized to mitigate fluctuations of active power exchange at POI caused by fast fluctuations in renewable power generation. Renewable Smoothing function of the microgrid controller sends a charging/discharging command to BESSs (at a higher frequency compared to Economic Dispatch) to keep the rate of change of active power within a pre-defined limit. In this example, the rate of change is selected as 0.12 MW/Min, and the initial SoC of batteries is considered 50%. The power generated by renewable sources, power exchange with utility, and power generated/absorbed by BESSs are depicted in Figure 8.

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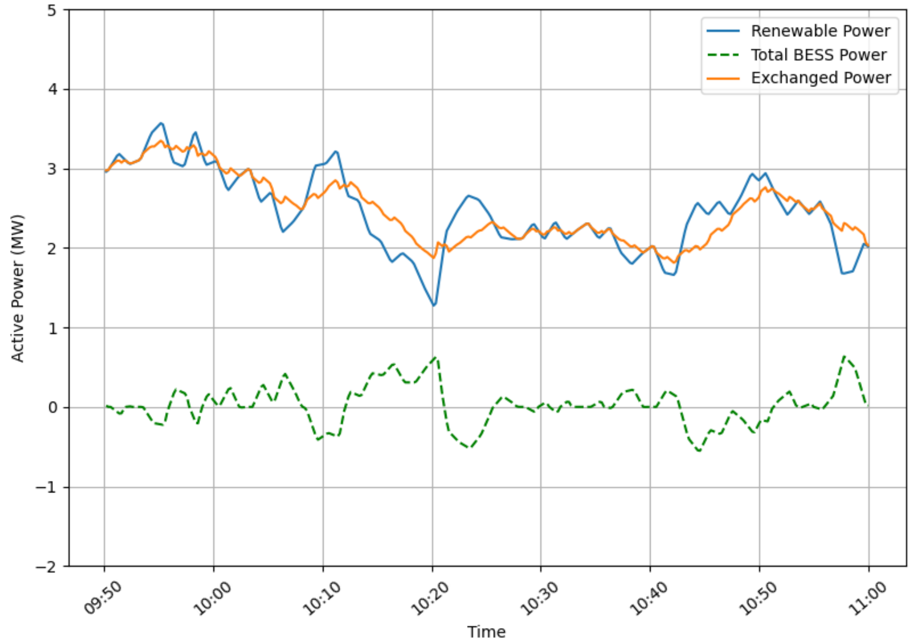

Figure 8 Example of Renewable Smoothing Functionality

Reactive Power Control

ETAP Controller can regulate voltage, reactive power, or power factor. There are several ways that the user can select the control mode and settings.

1. Fix setting: for instance, the control voltage of POI at a pre-defined setpoint. The setpoint can also be varied during operation by an external control such as ADMS.

2. Hourly schedule: e.g., control voltage between 7 am to 8 pm while control pf for other times. The schedule can also be varied during operation by ADMS.

The variable to be regulated (voltage, reactive power, or power factor) is selected. A ramp rate limiter can be enabled, limiting the total change in reactive power generation, and the rate can be varied by the ADMS or through HTTPS-based UI. If a new dispatch command from ADMS is received, the reactive power control logic will follow it and ignore the pre-defined schedule settings for the command duration.

A list of reactive power assets to prioritize participation is also embedded in the ETAP microgrid controller. For instance, users can utilize a generator, first, battery second, and renewables third to be controlled. The control function tracks the reference value and can be modified to obtain the desired response.

An example of reactive power control functionality of the microgrid controller is presented here. In this example, the microgrid controller regulates the voltage at the point of measurement (POM) or POI. An hourly schedule for the voltage is programmed in the controller such that at 9:00 am, the voltage reaches 100%, followed by an increase to 101% at 10:00 am, followed by a decrease to 98% at 11:00 am. The voltages for cases where reactive power control is enabled and for the case where this functionality is disabled are depicted in Figure 9. Blue line represents the case where reactive power control is disabled, while the red line shows the voltage when reactive power control function is enabled.

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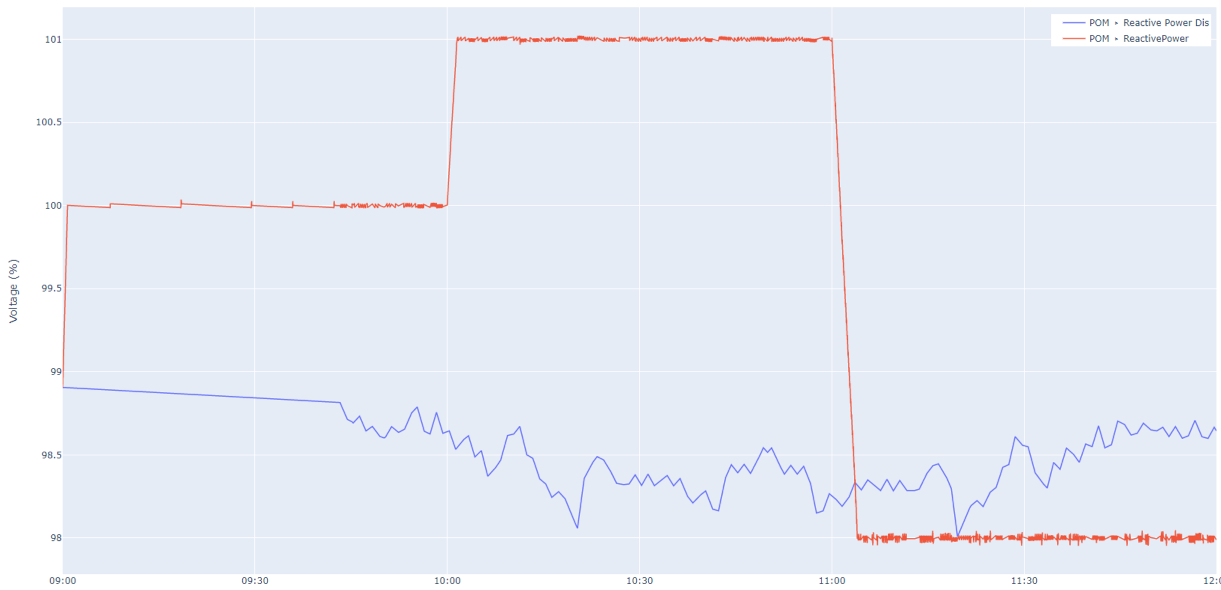

Figure 9 Voltages in Reactive Power Control functionality of Microgrid Controller (Scheduled Voltage Control)

Microgrid controller prioritizes reactive power assets based on a list provided by settings or external sources such as ADMS. In this example, switching capacitors, STATCOM, battery, and PV inverter are prioritized from high to low priority, respectively. Additionally, the rate of change in reactive power is regulated by employing a rate limiter (in this example, 0.6 Mvar/min). The reactive power exchange at POI is shown in Figure 10. According to this figure, the injection/absorption of reactive power at POI is limited by the defined rate limit. At each timeframe of the scheduled scheme, the microgrid controller can change its control logic and regulate voltage, reactive power, power factor, or reactive power based on the Q-V Curve.

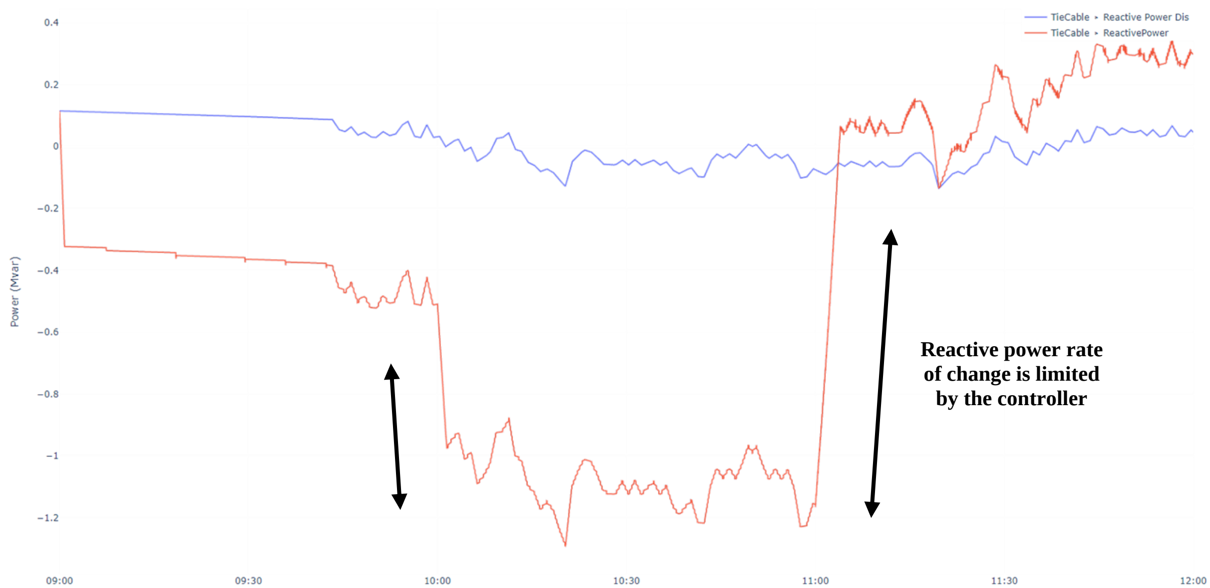

Figure 10 Reactive Power Exchange with POI when Reactive Power Control is disabled vs. enabled

Planned Islanding

Microgrid planned islanding is required to avoid loss of service to essential loads in case of loss of grid due to planned maintenance or outage. The ETAP microgrid controller offers Planned Islanding function responsible for

1- responding to planned islanding request from supervisory level such as ADMS,

2- prepare microgrid for planned islanding and

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3- island the microgrid by tripping a circuit breaker at POI.

Planned Islanding function, based on a pre-scheduled outage plan, performs an optimization logic to

1- determine an optimal load/generation shedding strategy and DER dispatch for net-zero power exchange at POI,

2- dispatch energy storage to accumulate enough energy before islanding, and

3- dispatch the strategy before planned islanding time and once ready island the microgrid.

The ETAP microgrid controller continuously receives the updated status of the microgrid load, generation, and storage units. In case of a planned islanding formation, the microgrid controller based on the start time and the duration of the islanding operation; forecasted load and generation profile of the assets; capacity of a backup generator; and the current state of charge of the storage units runs an optimization logic ahead of time to minimize the number of loads needs to be shed during the islanding operation. The microgrid controller dispatches the storage units to start or continue charging to increase their SoC and starts running the backup generator if required.

In case that the microgrid controller cannot maintain the required load and generation margins, it will not proceed with the islanding formation. Otherwise, it dispatches the loads, including load shedding, if necessary, according to the preset priority, sources, and storage units to minimize the exchange of real and reactive power at the point of interconnection (POI) to facilitate the transition to islanded mode. For the controllable loads, the microgrid controller sends commands to change their reference set points. For uncontrollable loads, the MCS will open/close their circuit breakers or switches if needed. At this stage, the microgrid controller notifies the system operator of its readiness to island. Once approval is received, it trips the POI CB and then communicates with the DER with grid forming capability to change its control mode from grid following to grid forming. The microgrid controller also communicates with protection relays and IEDs to change their active protection setting group. The microgrid controller switches to the islanded mode, and the islanded operation function gets activated while the planned islanding function gets deactivated.

Following IEEE 1547-2018, Sections 8.2.2 and 8.2.4, ETAP microgrid controller activates/enables the DER "intentional island" mode during a transition to island mode. ETAP microgrid controller notifies microgrid DERs that an island event is happening, so the transition to "intentional island" mode can proceed.

Figure 11 shows the performance of the ETAP microgrid controller under a planned islanding scenario. In this case, the MCS receives a planned islanding formation schedule from the grid operator for 2 hours at 19:30. Based on the remaining time to the scheduled islanding formation, the MCS, the duration of islanding operation, the forecasted load and generation profiles, and the current SoC of storages, runs an optimization problem to determine the required SoC and the time to start charging the storages. As shown in Plot B, the storages start to charge at 16:20, and their SoC reaches the desired level around 18:45. The MCS, based on the storages and generators output power ramp rates, determines the time to start (ramp-up) the storages and generators (if required) and sends commands to ramp up the sources at 18:55 (see Plots A and C). Simultaneously, the MCS runs the transition to islanded mode logic to determine the list of the loads or generation units to be shed (if required) according to sheddable loads/generations categories. As shown in Plot D, the MCS sheds some loads at 18:55 to minimize the exchange of real and reactive powers at POI and facilitates the transition to islanded mode.

As shown in Plots E and F, at 19:20 (10 minutes before the scheduled islanding formation start time), the import real and reactive powers at POI gradually drop to zero, and the microgrid becomes ready to switch to an islanded mode of operation.

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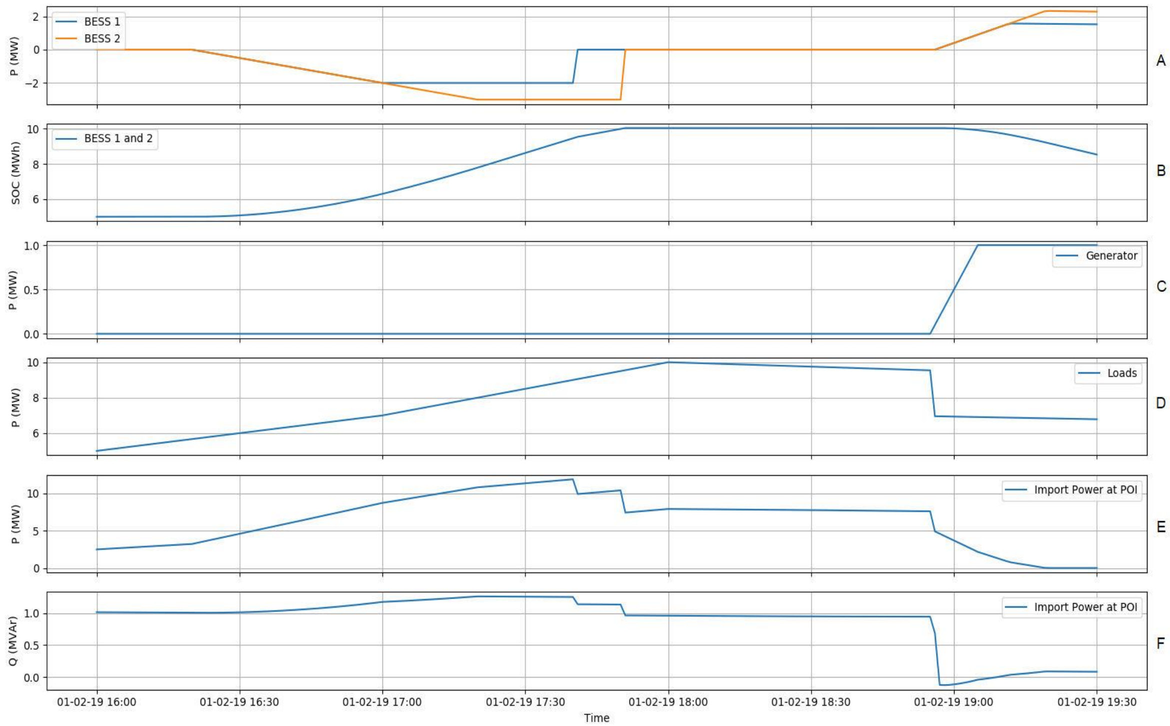

Figure 11 Example of ETAP Microgrid Planned Islanding Functionality

Unplanned Islanding

ETAP offers an Unplanned Islanding function that continuously devises the optimal strategy based on the latest microgrid real-time condition to make an unexpected transition to islanded mode possible. The optimal strategy typically includes load shedding, the start of a backup generator, switch the grid-forming device to grid forming mode. This function continuously updates unplanned islanding strategy every few seconds that can be set by the user while the system is in grid-connected mode. This islanding strategy is continuously transmitted to a high-speed real-time controller that is typically the same as Gateway used to communicate with DERs and loads. Simple interlocking logic will be developed in the real controller/Gateway to apply the pre-calculated islanding strategy to immediately detect an islanded condition or trip signal to POI CB to facilitate an ultra-fast remedial action to facilitate a transition to an islanded mode of operation.

The ETAP microgrid control system continuously monitors the status of the loads, generation, and storage units. Based on the current load and generation profiles of the assets; and the current state of charge of the storage units, the MCS continuously runs an optimization logic to calculate the amount of load/generation needs to be shed according to a pre-specified prioritization categorization.

ETAP microgrid controller continuously communicates and provides the list of required actions to the real-time controller to be prepared if an outage occurs at that specific time. Once real-time controller/Gateway senses that grid connection is lost, it immediately initiates a pre-provided action plan such as sending a command to the unit(s) with grid forming capability to change its status from grid following to grid forming operation mode and implementing load shedding based on a. The unplanned strategy includes shedding the least priority loads in a way to satisfy the load/generation balance as well as maintain the required reserve margins. For controllable loads, the MCS will send commands to change their reference set points, and for uncontrollable loads, the controller will send trip or transfer-trip commands.

ETAP microgrid controller monitors the SoC of storages and based their pre-specified threshold values, manages the storage, and, if required, it will replace storages with the backup generator. The MCS will check the assets' status and dispatch the units to maintain the required load and generation margins when the microgrid system successfully switched to the islanded mode of operation. Suppose the existing SoC of the storages is less than a pre-specified threshold or an enormous gap between demand and generation. In that case, the controller will shut down the microgrid and initiate a black start.

ETAP microgrid controller control commands critical to the integrity of the microgrid during islanding events are prioritized over ADMS commands if a conflict arises.

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Figure 12 summarizes the performance of the ETAP microgrid controller under an unplanned islanding condition. In this case, a fault occurs on the utility side at 1 sec. The relay at POI detects the fault and trips POI CB at 1.02 sec. The Gateway RT Controller receives a transfer trip signal from the POI relay at 1.04 sec. It initiates load shedding and switching battery to grid forming at 1.055 sec based on a preconfigured action plan devised by MCS before fault occurrence. An alternative approach can be set to initiate unplanned islanding remedial action once CB at MGPOI is open or utility exchange power is suddenly lost. In this scenario, MGPOI CB is also tripped by the remedial action. The load relay/controller and battery receive commands from Gateway RT Controller, and thereby MGPOI CB trips at 1.07 sec. The battery (BESS 2) switches to the grid forming at 1.08 sec. The load circuit breakers trip at 1.12 sec to satisfy the load/generation balance and maintain the required reserve margins (see Figure 13). As shown in Figure 14, the microgrid frequency and voltage reach the nominal values once the microgrid successfully transited to the islanded condition.

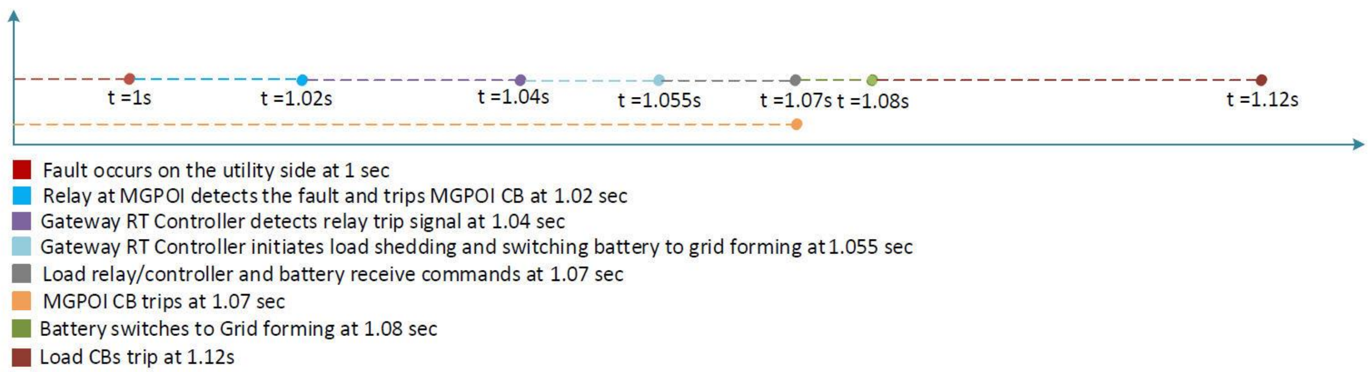

Figure 12 ETAP Microgrid Controller Unplanned Islanding Formation Function

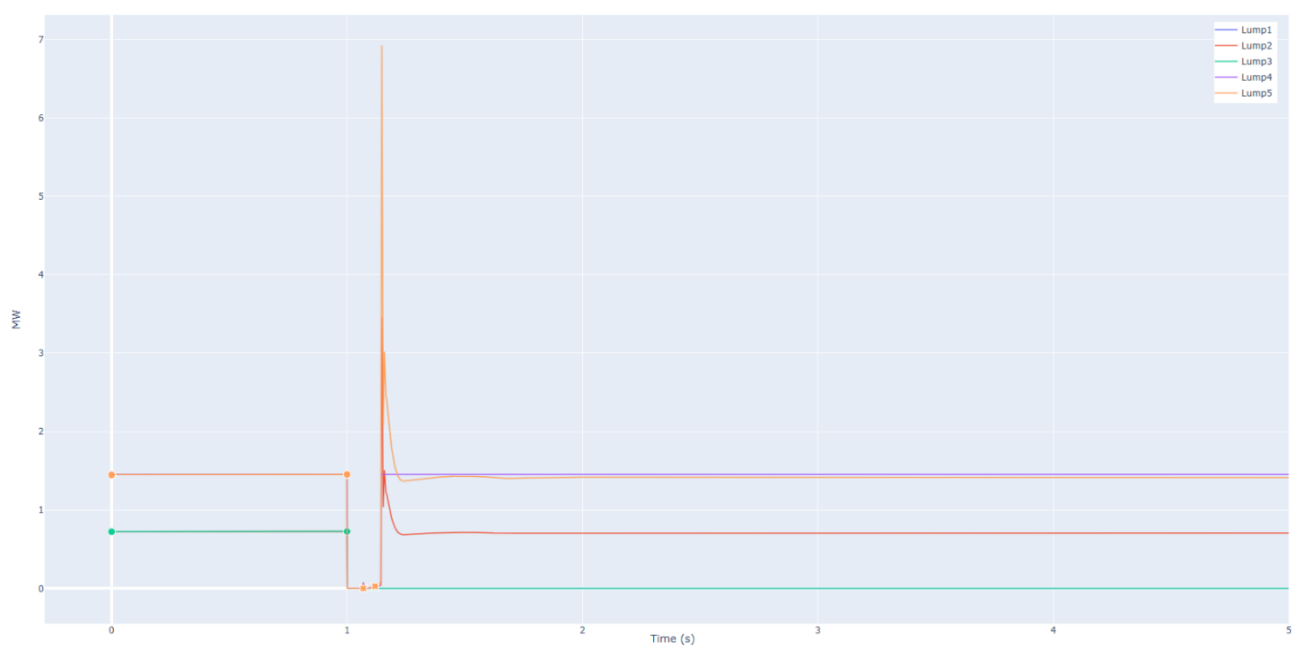

Figure 13 Unplanned Islanding Function of Microgrid Controller – Loads

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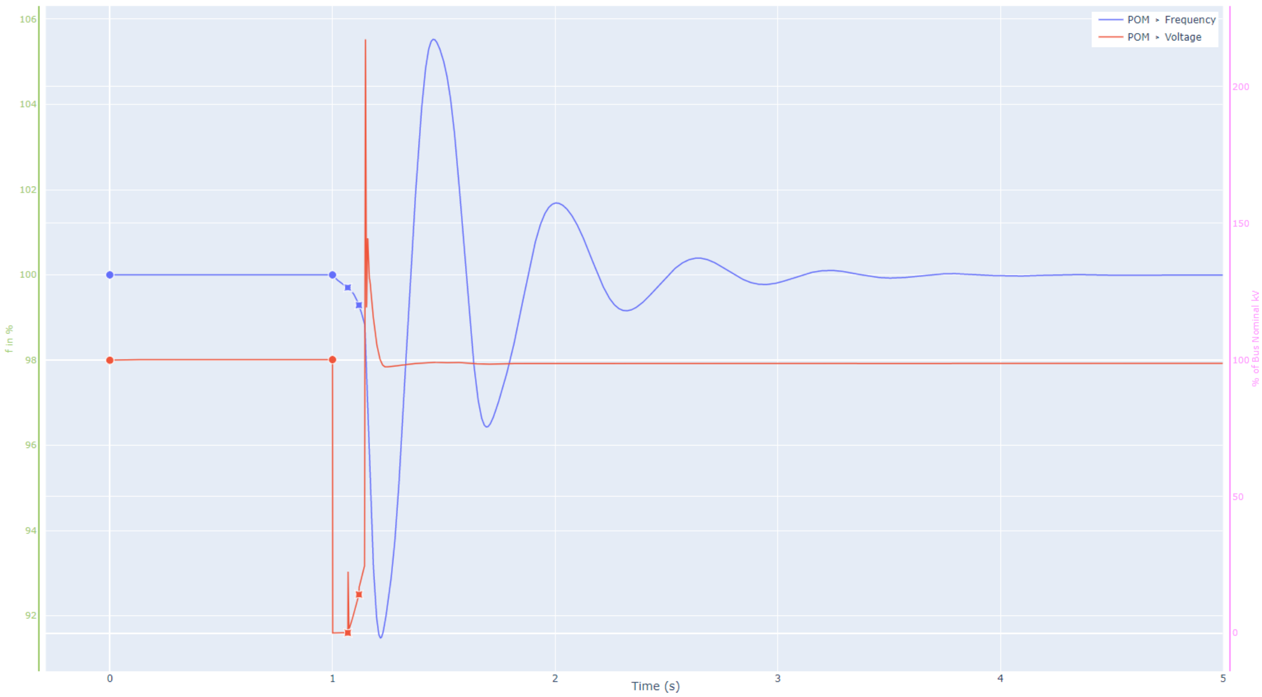

Figure 14 Unplanned Islanding Function of Microgrid Controller – POM Bus Voltage and Frequency

Islanding Operation

Once the microgrid is successfully transitioned to the islanded mode either through planned or unplanned islanding or black start, this function gets activated to maintain

1- sufficient reserve margin on Grid-forming storage or isochronous generator and

2- acceptable voltage profile across the microgrid.

This is done by dispatching the active power of non-grid forming/isochronous DERs combined with load shedding or renewable curtailment as needed. In microgrids with all droop-based DERs, the microgrid controller dispatches assets to maintain reserve margin across droop-based assets. DERs with or without frequency support are considered to ensure the reliability of operation. Different protection setting groups based on preconfigured settings can be employed to adapt the protection system depending on which loads and sources are available at the time of operation.

In the case of microgrids with substantial DER and storage capacity, an optimization algorithm is executed every few seconds or minutes that can be set by the user to either

1- minimize the cost of operation,

2- maximize the duration of islanding,

3- minimize the amount of load shedding, and

4- minimize emission

Both active and reactive dispatch power commands are applied through a ramp rate controller to ensure the stability of the delicate islanded system.

The optimization algorithm considers:

1. Preconfigured/site-specific information such as load prioritization information
2. Contracted DER load and generation sizes and capabilities (nameplate ratings and settings)
3. V/f source capabilities including state of charge if the battery (or expected state of charge if a planned outage)
4. Forecasted weather information (if available and applicable)

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5. Forecasted load and generation
6. Preconfigured operational modes (cost-based, emissions based, reliability-based)
7. DER availability

ETAP microgrid controller in islanded mode has supervisory control, and loss of communication with DER or the entire system does not have an immediate adverse impact. However, as loads and renewable generations vary, dispatchable assets must be adjusted to maintain a proper reserve margin. Hence, microgrid runs for as long as power balance cannot be maintained, resulting in over/under frequency or voltage protection operation.

In case of a fault and isolation of a part of the islanded microgrid, the ETAP microgrid controller senses the fault by monitoring protective devices such as relays and breakers. Upon losing part of the system, the ETAP microgrid controller first evaluates if enough energy resources and loads/generation can be shed to maintain the microgrid's reserve margin and stable operation. If yes, an optimization algorithm will be executed to determine the optimal DER set points; otherwise, an additional load/generation shedding will be applied to maintain the balance of the system.

In an islanded operation, the ETAP microgrid controller can adjust the voltage reference and power factor of the grid forming or isochronous generator by adjusting the reactive power of other DERs and reactive power resources. Ramp rate control for reactive power is also available in this mode, as shown below.

Forced Blackout

The outage in the microgrid can be caused by one of the following reasons:

1. After the loss of the grid and during the unplanned islanding scheme, the controller concludes that the microgrid cannot be sustained, and a blackout is enforced.

2. After the loss of the grid and during the planned islanding scheme, the controller concludes that the microgrid cannot be sustained, and a blackout is enforced.

3. In the transition from islanded mode to grid-connected mode, the controller concludes that resynchronization is not feasible, or resynchronization fails a few times. In this case, a blackout is enforced, and the Cold Load Pickup procedure is initiated after confirmation of ADMS.

In all three cases, the controller initiates enforced blackout by activating the enforced blackout function to energize the microgrid and create an island. To de-energize the microgrid, the ETAP microgrid controller opens a series of circuit breakers based on a pre-determined scheme. The sequence of circuit breakers is provided to the microgrid controller as input settings.

Black Start

Once the microgrid is completely de-energized either by itself or through enforced blackout function, the black start function gets activated to form an islanded microgrid if the grid is not available. In the black start function, the user can define multiple V/f sources and their priorities through settings. The desired reserve margin of the microgrid for this mode of operation can be set as well. The desired reserve margin is defined as the difference between the DER rating/generation (depending on if renewable or not) and loading at each moment. During the black start process, the controller employs the V/F source with higher priority for a black start unless one of the following conditions occurs.

1. If the SoC of energy storage selected as the primary V/f source is close to its maximum or minimum limit, then other DERs will be employed.

2. If DER has a minimum generation setting and it is required to generate less power than this minimum value, other DERs will be employed.

Once the V/f source is determined, the ETAP microgrid controller commands the source to start to form a grid. Next, based on a priority list of loads defined by the operator in the settings, the microgrid starts the load with the highest priority and closes its circuit breaker. Based on the rating of DERs and the latest measurement before an outage, the controller re-calculates the reserve margin of the microgrid and applies the following logic:

1. From all the available DERs, the one that reduces the reserve margin the most is selected. Initially, DER's power is set to its minimum possible value (zero if possible). Once energized, the controller sends a signal to close its circuit breaker and dispatches all the system's DERs. In the dispatch, a higher priority is given to removing curtailment from renewable sources.

2. If adding a DER increases the reserve margin, the controller moves to the next step.

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3. The next load from the priority list is selected and is reconnected to the microgrid. MCS re-calculates the reserve margin and starts and reconnects another DER if needed based on the above logic. This procedure is continued until all the loads in the microgrid are energized.

By following the logic mentioned above, the controller optimally determines which generation assets should be added to minimize the desired reserve margin deviation. Once all the essential loads in the system are energized as much as possible, the microgrid controller switches to islanded mode. If the grid is available at any time, the microgrid controller changes its control mode to resynchronization mode if permitted by system ADMS; otherwise, it follows the islanded control scheme.

Reactive power resources are also considered and dispatched as part of the black start logic. For nested microgrids, the ETAP microgrid controller can perform a black start island formation for the entire microgrid, or energize each nested microgrid, separately. If the entire microgrid is set to form an island using black start capability, the nested microgrid's black start function is overridden.

Reconnect

ETAP microgrid controller offers a supervisory reconnect function that coordinates with sync-check relay or protection function at MGPOI and system operator and other assets within the microgrid to perform the grid resynchronization. ETAP microgrid controller can be set to limit the permissive period for resynchronization. This setting can be changed remotely, as well. If resynchronization fails, the microgrid controller waits for "Interval time" before another try of resynchronization. ETAP microgrid controller can be set to check grid status and stability by monitoring voltage level, voltage change (dv/dt), and (Δf per min) before initiating resynchronization.

After receiving all confirmation required by the TSO or DNO, the synch-check relay gets activated to initiate resynchronization. If voltage magnitude needs to be increased, reactive power resources will be used to increase the voltage level; if frequency needs to be slightly changed to create an opportunity for the other side angles to match, the active power of DERs or frequency of grid forming source will be varied to help matching voltage angles of both sides of POI.

Once the microgrid is successfully re-synchronized, As shown below, several tasks will occur:

1. new relay setting group will be dispatched.
2. low priority (non-essential) loads will be restored.
3. ADMS will be informed regarding successful resynchronization.

If resynchronization fails after preconfigured attempts, the controller activates the Forced Blackout function and then try Cold Load Pickup.

Web Interface

ETAP offers a web-based user interface (UI) to provide high-level access to the microgrid controller settings, metering, controls, records, and maintenance. The interface supports HTTPS, multiple concurrent users with pre-defined restricted and secure role-based access for each user. This interface is available from the operator network. All microgrid controller settings that can be changed can be monitored and edited through this interface. Users can also configure control function settings such as optimization scheme settings.

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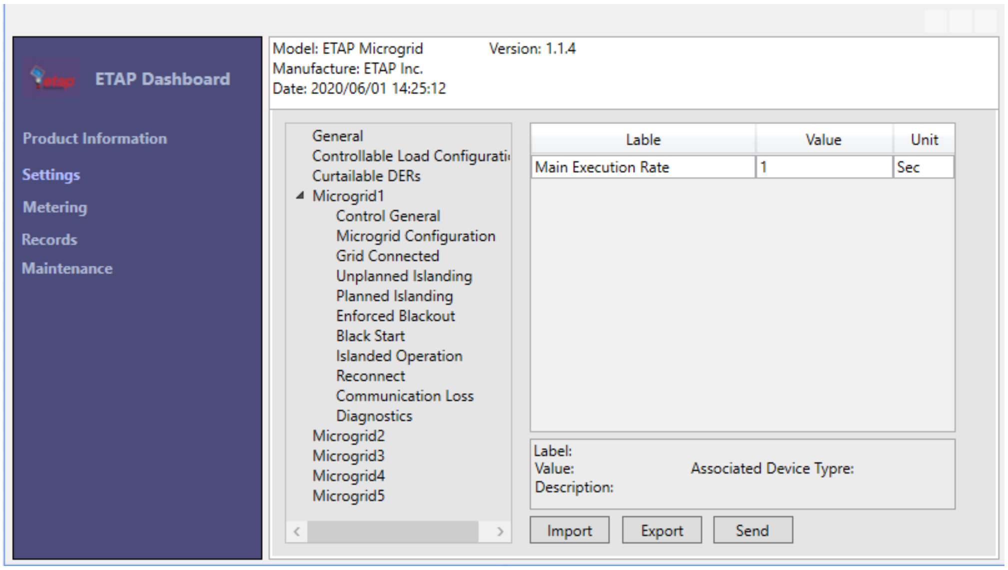

Figure 15 Settings

Users can select and plot the real-time trends of the input signals of the controller. Moreover, the information about switches and protection devices' status can be observed on the metering page. ETAP microgrid controller UI supports configurations to dispatch controls to individual DERs or groups of DERs based on configured DER type (PV, BESS, EV, etc.) and ownership model.

Figure 16 Metering

Users can access the list of all measurements, logs, events, reports, and waveforms from this UI. This information can be used to manage, test, and troubleshoot the microgrid controller. The user can also download the log files and check the status of the system.

ETAP microgrid controller can maintain multiple settings and configuration as well as function library data while one is active at a time. User can upload new or activate from previous versions; stop/start and restart the MCS from this UI.

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Load and Generation Forecast

Microgrid supervisory control depends on load and generation forecasts to optimize the utilization of DERs. ETAP Short-Term Load Forecasting (STLF) is an ideal tool for microgrid applications to forecast future short-term loading in the system reliably. ETAP Load Forecasting uses the following inputs:

1. Historical Loading
2. Historical Temperature
3. Historical Relative Humidity
4. Forecast Temperature
5. Forecast Relative Humidity

The ETAP Load Forecasting Manager application is used to set, configure, and run the Load Forecasting studies. The Load Forecasting Manager allows the user to set the scheduled automatic studies as well as view the study inputs and outputs graphically.

1. Display real-time and forecasted load in the ETAP Real-Time trending and web applications
2. Utilize Real-Time weather and loading data for revising the forecast
3. Utilize historical data or user-defined patterns stored in a library
4. Import weather information downloaded from a weather data API over the internet
5. Unlimited forecast views

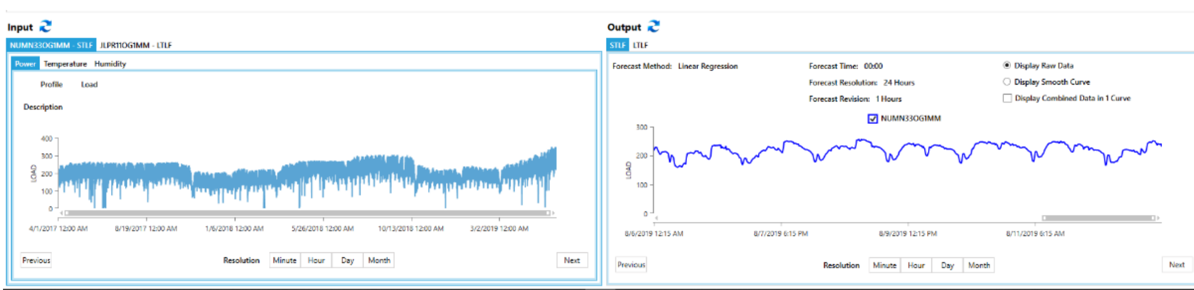

Figure 17 Load Forecasting

ETAP microgrid controller uses ETAP Load Forecasting described above to forecast load. Solar generation forecast is performed within ETAP microgrid Controller using solar irradiance calculated based on geographical location, temperature forecast, weather forecast, and historical generation data. Wind generation forecast is performed based on the system output power forecasting by using historical power data.

ETAP microgrid controller and ETAP load forecast manager can receive weather forecasts from ADMS or other systems. Internal load and generation forecast can be replaced by using load/generation forecast from an external source such as ADMS using an API or DNP3 protocol.

Hardware

The ETAP microgrid controller is hardware-agnostic. The key features of host hardware are listed below. For mini-grid applications where more straightforward control logic and inexpensive hardware are required, several options are available.

- Rugged design
- IP40 ingress protection
- Different I/O and communications buses
- DNP3, rest of the protocols supported through iCE™
- Supports Linux and Windows

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Figure 18 Hardware for Microgrid Applications

Conclusion

In conclusion, first, the microgrid controller's important role in the microgrid control system was introduced. Various challenges of development, testing, and validation were discussed. It is difficult to optimally fit a generic microgrid controller that is designed to support certain features to every application. On the other hand, programming an appliance-based controller to realize a dedicated control function for each microgrid application is also very costly and requires an extensive expert engineering effort. Also, a microgrid controller accurate model or digital twin is required to properly perform a feasibility study and optimal sizing of microgrid resources in advance. Microgrid controller vendors do not provide such a model in most cases.

This paper presented an ETAP microgrid control system founded based on three advanced technologies: 1- Model-driven approach, 2- Digital Twin, and 3 –Software development framework for power system applications. Using this technology, ETAP can customize or enhance its controller with minimum effort in its mature & nuclear grade power system software simulation environment. ETAP Microgrid Controller offers several control functions, including Optimal Dispatch, Planned Islanding, Unplanned Islanding, Islanding Operation, Black Start, Reconnect, Renewable Smoothing, and Reactive Power Control to manage microgrid in both grid-connected and islanded modes as well as facilitating a seamless transition between both modes.

References

[1] M. R. Dadash Zadeh, A. Mazloomzadeh, H. Ghaffarzadeh, and H. Castro, "Model-Driven Microgrid Controller," 2019 FISE-IEEE/CIGRE Conference - Living the energy Transition (FISE/CIGRE), Medellin, Colombia, 2019.

[2] "IEEE Standard for the Specification of Microgrid Controllers," in IEEE Std 2030.7-2017, pp.1-43, 23 Apr. 2018.

[3] M. R. Dadash Zadeh, F. M. Uriarte, "Programmable Microgrid Control System," filed for a US patent, 2019.

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