DEVELOPMENT OF A MICROGRID CONTROLLER FOR A REMOTE OFF-GRID POWER SYSTEM IN NORTHERN CANADA AND ITS EVALUATION USING HARDWARE-IN-THE-LOOP SIMULATIONS

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OUTLINE

- Background
- Overview of microgrid control systems
- Aims
- Off-grid power system
- Power Management System - Dispatch functions
- Power Management System – Transition function
- Implementation
- CHIL test setup
- Results
- Conclusions

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McMath High Voltage Lab (M^2HV)

Power System Simulation

Power System Dynamics and Stability

Renewable Energy Interface and Grid Automation (RIGA)

Power Electronics and Energy Conversion (AMPS)

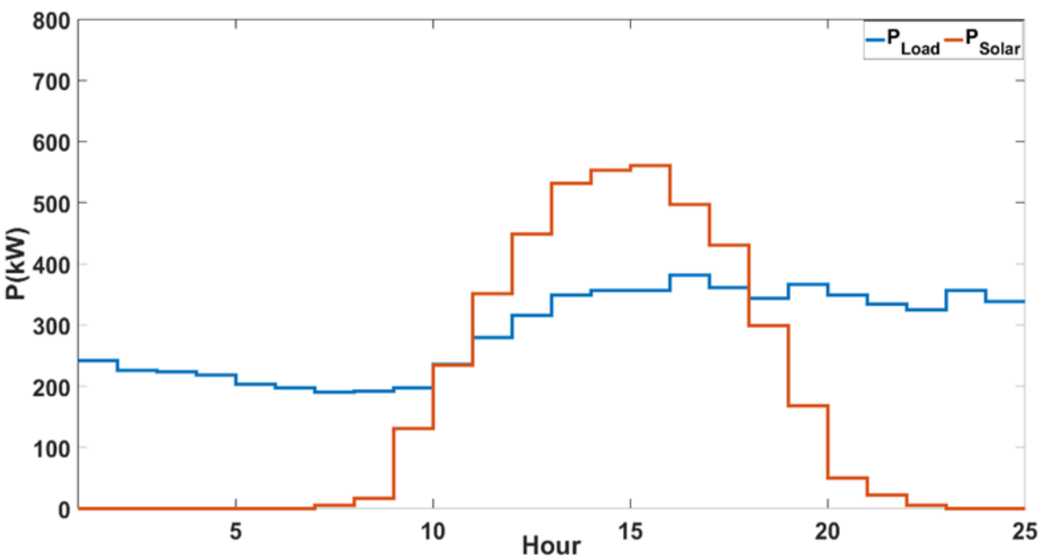
OFF-GRID POWER SYSTEMS IN NORTHERN CANADA

http://www.crossroads.ca/northlands-first-nations-lac-brochet-manitoba/

http://www.cogua.ca/history/manitoba_systems.htm

- Many communities lacks year-around land transportation
  - Rely on winter roads for fuel and goods transportation
- Primarily rely on diesel generation for electricity.
  - Environmental risks related to diesel transportation and storage.
  - Emissions and spills during use.
- Utilization of local renewable energy sources can reduce the reliance on diesel.
  - Solar energy, Bio-mass, Mini-hydro, etc.
- PV-Diesel energy systems have emerged as one potential solution

PV-DIESEL OFF-GRID POWER SYSTEMS



- Diesel generators operating at undesirable output levels can result in low efficiency and loss of life.
- PV power curtailment to accommodate minimum diesel generation makes investments in PV unattractive.
- Energy storage with proper energy management strategy can improve the situation

PV-DIESEL-BATTERY MICROGRIDS

- Battery energy storage (BES) is currently the technologically most feasible option.
- Energy management system of a PV-Diesel-Battery microgrid optimizes the operation over period of time such as 24 hours.
  - Minimizes operating costs, emissions, and component degradation
  - Maximizes the utilization of renewable sources
- Two possible operating modes
  - Diesel generators forms the grid
  - BES system forms the grid
- A power management system is required to ensure stable operation of the microgrid.
  - Short-term power balance, seamless transition between operating modes
  - Secondary voltage and frequency control

MICROGRID CONTROL SYSTEM

- A microgrid control system controls the microgrid assets to achieve multiple objectives of energy and power management systems.

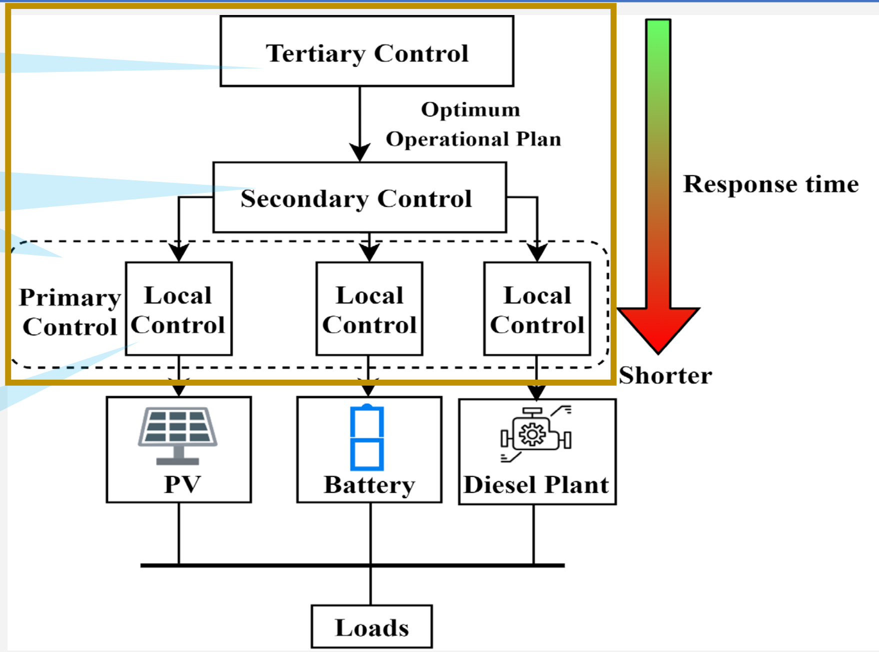
Microgrid Control System Hierarchical levels

Optimizes the overall operation

- Appropriate command and reference signals for the primary level
- Manage transitions

IEEE 2030.7-2017 standard outlines the specific requirements and tasks of microgrid controllers to help the development of microgrid control system functions

- Maintain stable voltage and frequency
- PQ and Vf control

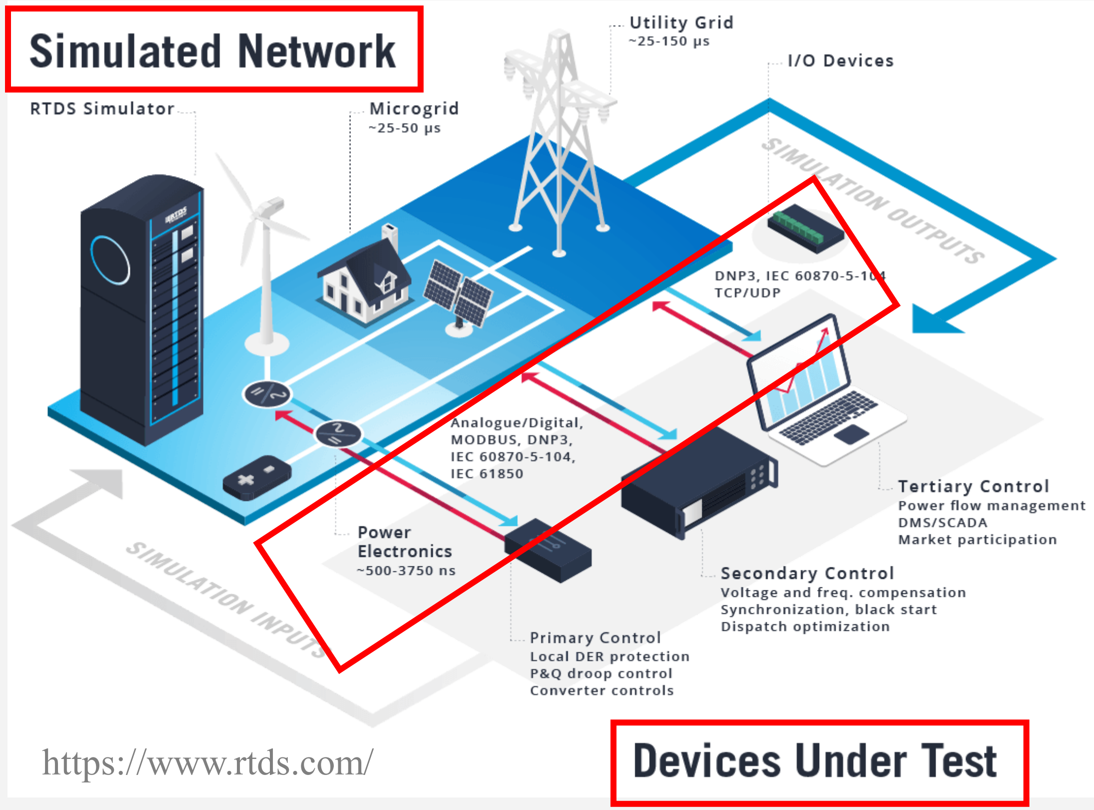


MICROGRID CONTROL SYSTEM TESTING

- IEEE 2030.8-2018 standard describes test scenarios that can be used to assess whether a microgrid controller complies with the requirements specified in IEEE 2030.7-2017 standard.
- Different techniques have been used to assess the performance of microgrid control systems:
  - Pure Simulation
  - Hardware Test Benches
  - Power Hardware in the Loop (PHIL)
  - Controller Hardware in the Loop (CHIL)

MICROGRID CONTROL SYSTEM TESTING

- Hardware in the loop (both CHIL and PHIL) has become a popular method to validate microgrid control systems.
  - Closer real world testing conditions
  - Perform wide array of scenarios



- HIL testbeds could facilitate faster and more accurate design iterations
  - Save engineering time
  - Cost-effective

PROBLEM STATEMENT AND AIMS

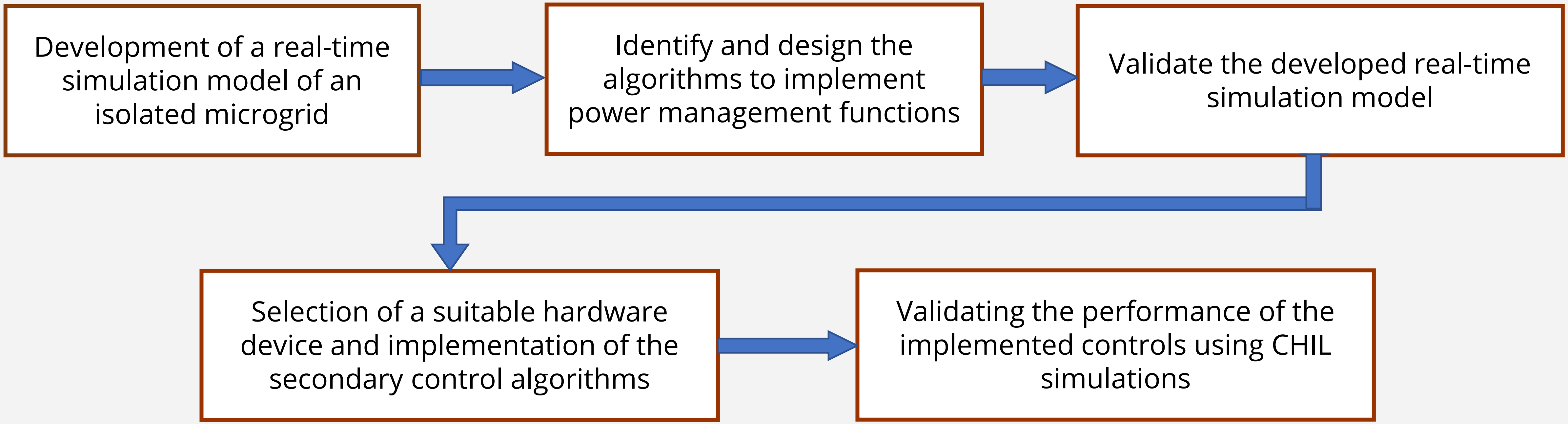
Problem Statement

- A microgrid controller needs to be customized to the given system and underlying requirements
- Majority of microgrid CHIL testbeds are implemented for microgrids connected to stiff grids.

Aims

- To develop a microgrid power management system for an isolated power system consisting of PV, diesel generation, and BES.
- Setup a CHIL simulation setup for testing the microgrid power management system

METHODOLOGY

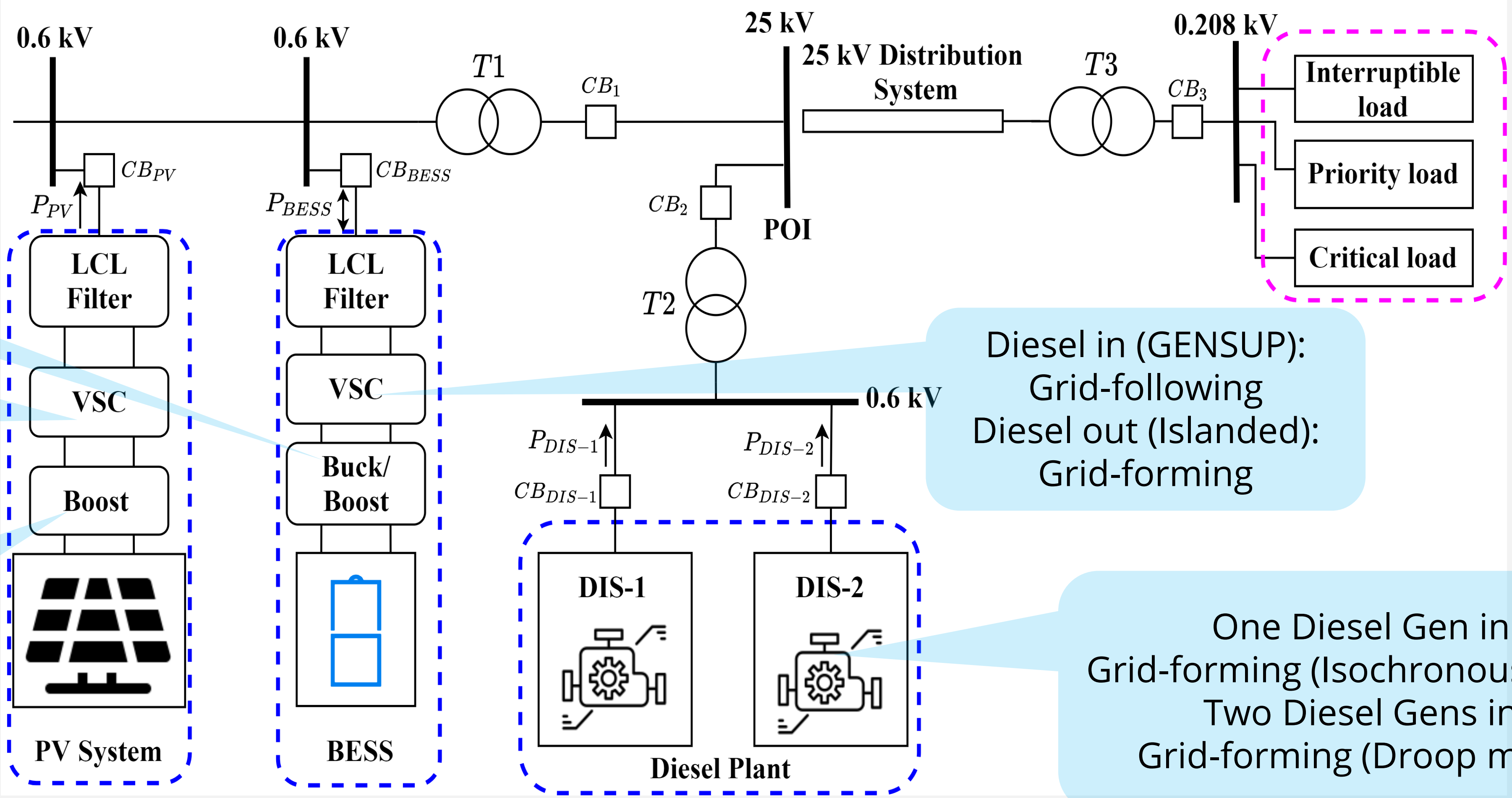


MICROGRID TEST SYSTEM

DC-link voltage regulation

Diesel in & Out: Grid-following

PV output power regulation

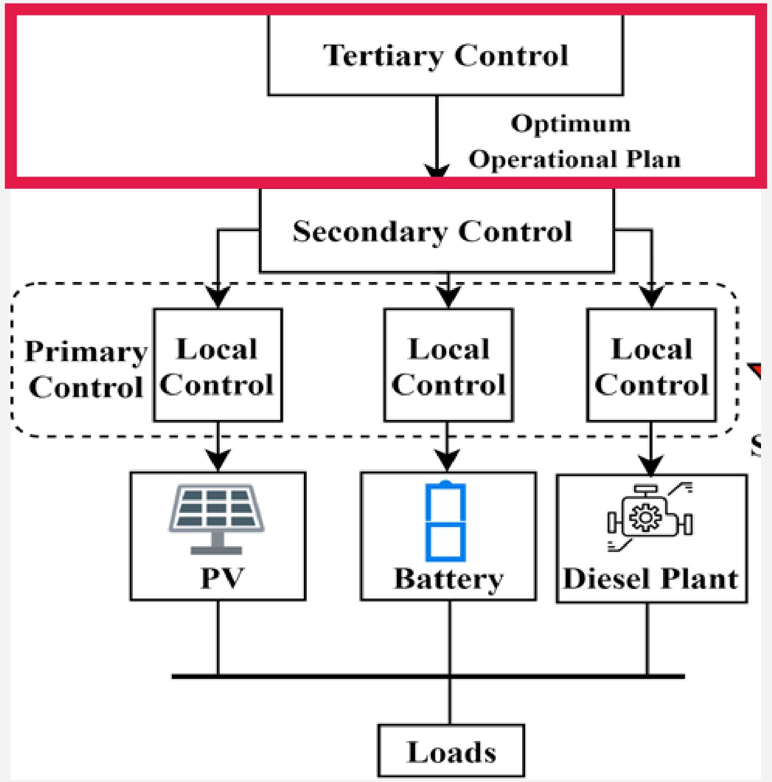


Diesel in (GENSUP): Grid-following
Diesel out (Islanded): Grid-forming

One Diesel Gen in: Grid-forming (Isochronous mode)
Two Diesel Gens in: Grid-forming (Droop mode)

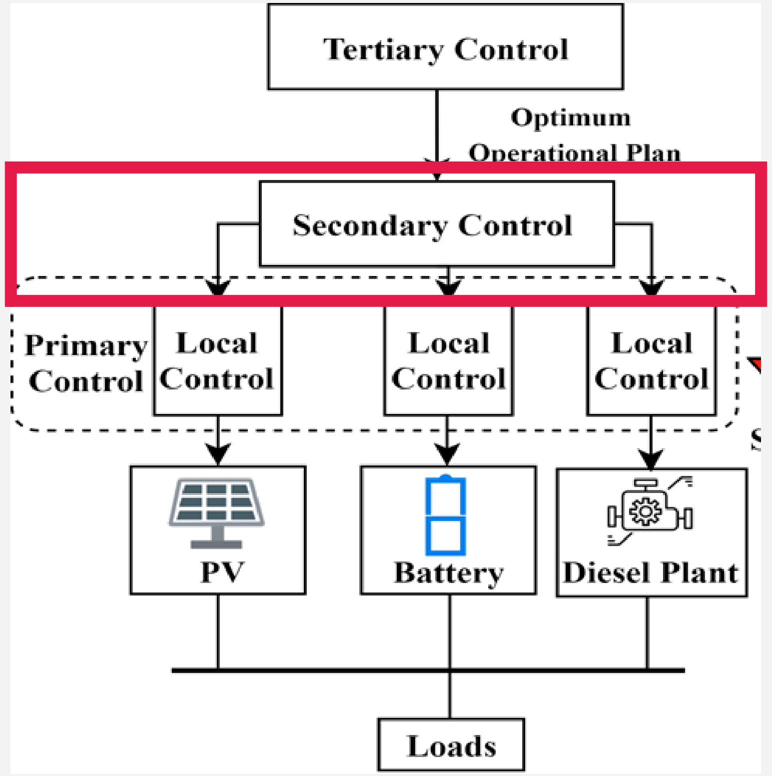
ENERGY MANAGEMENT SYSTEM (EMS)

- EMS uses an optimization framework to obtain the minimum daily costs and emissions.
- For the considered control horizon, the derived optimum operational plan suggests:
  - Power commands for the two diesel generators along with their on/off status
  - Hourly power commands for the battery unit
- EMS adjusts the derived operational plan at regular intervals to compensate for forecast errors
  - Uses a Receding Horizon Model Predictive Control framework.



POWER MANAGEMENT SYSTEM (PMS)

- IEEE 2030.7-2017 states dispatch and transition functions as the core level functions of a microgrid controller.
- Dispatch function
  - Balances power generation and demand under various operating conditions
  - Re-dispatches DERs according to the changes in load and generation
  - Follow the optimum operational plan
- Transition function
  - Manage transitions of the microgrid (reconnection, planned islanding, unplanned islanding)
  - Switch the dispatch function into different modes



PMS: DISPATCH FUNCTION

- The designed dispatch strategy integrates the following optimum control signals coming from an optimization framework:
- start/stop signals for the diesel generators (U_{DIS-1}^{EMS}, U_{DIS-2}^{EMS})
- BESS power reference (P_{BESS}^{EMS})
- Dispatch strategy is based on the constraints summarized in Table 1.

$P_{DIS-n} > 0.3P_{DIS-n}^{rated}$
Fuel efficiency

$P_{RGC} = K_L P_L + K_{PV} P_{PV}$
Deal with random nature of PV and load

Table 1: Constraints of dispatch function

Parameters	Criteria
BESS	SOC Limitations: $SOC_{min} \leq SOC \leq SOC_{max}$ Active Power Limitation : $P_{BESS}^{min} < P_{BESS} < P_{BESS}^{max}$
Diesel Plant	Active Power Limitation: $0.3P_{DIS-n}^{rated} \leq P_{DIS-n} \leq P_{DIS-n}^{rated}$
Reserve Generation Capacity (RGC)	Reserve Power Limitation: $P_{RGC} \geq P_{Available} - P_{Load}$

PMS: GENSUP DISPATCH

Minimally adjust BESS power reference.

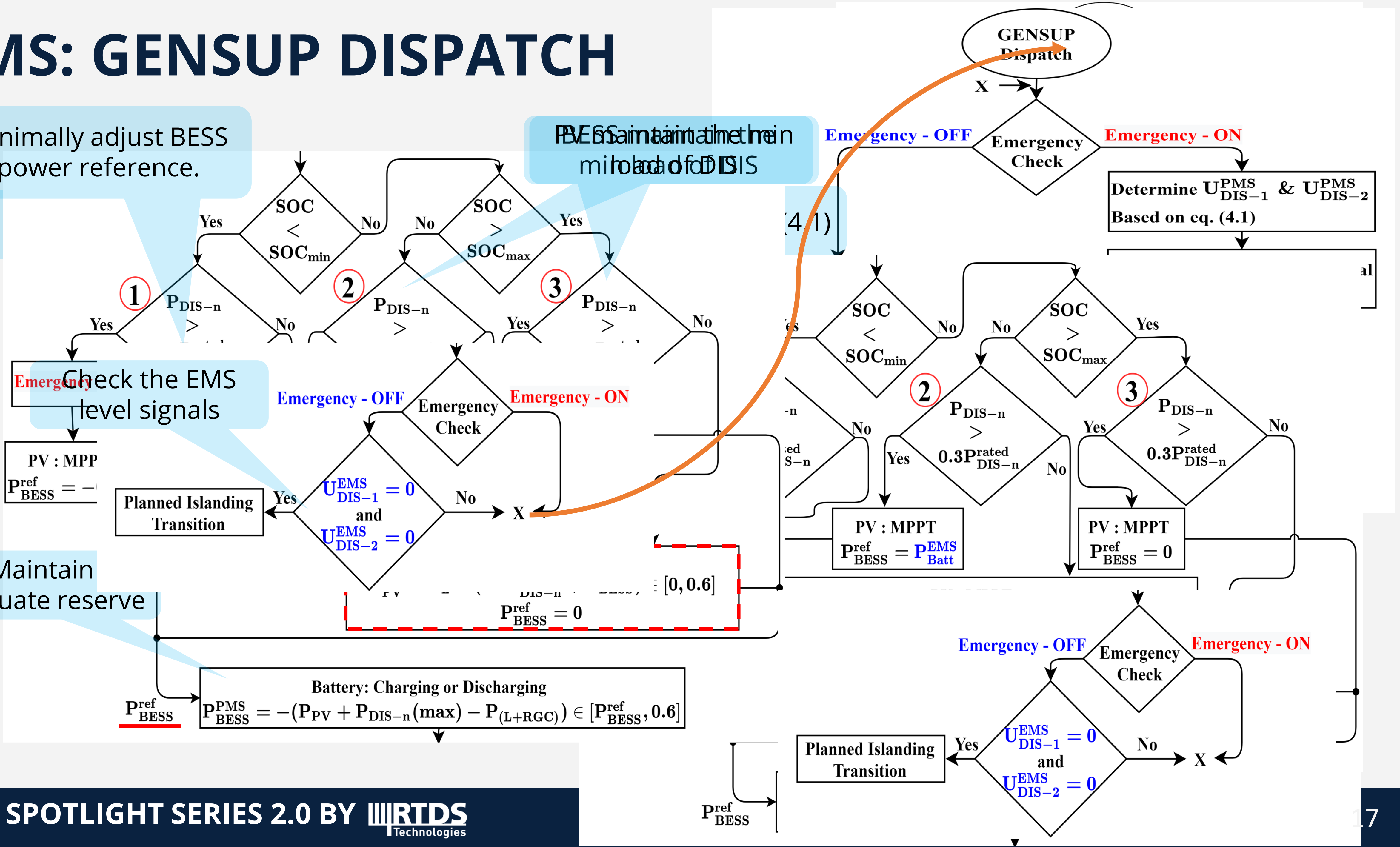
Fol

BESS maintain the min load of DIS

(4.1)

Check the EMS level signals

Maintain adequate reserve



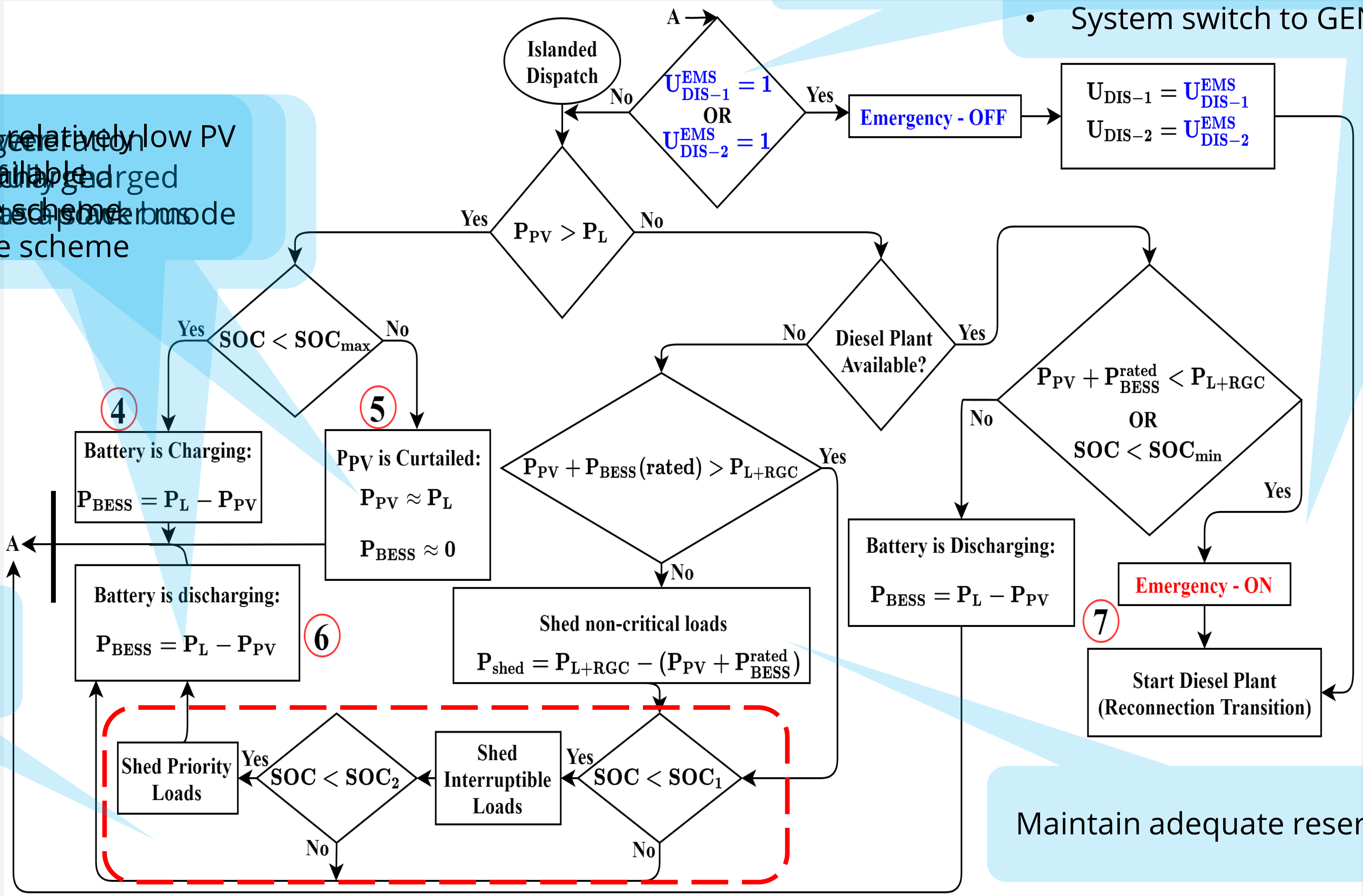
PMS: ISLANDED DISPATCH

System checks the EMS transition signals

- sustained period of high load
- Power reserve is violated
- System switch to GENSUP mode

- High load and relatively low PV
- Diesel is unavailable
- Power reserve scheme
- Energy reserve scheme

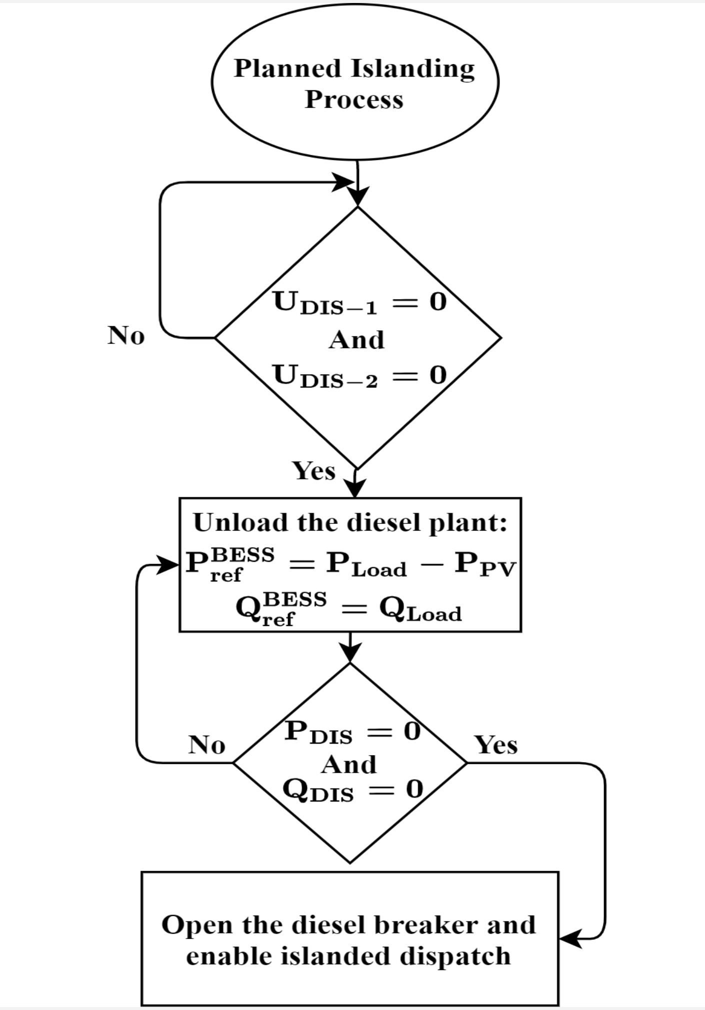
- Excessive PV generation
- Battery is not fully charged



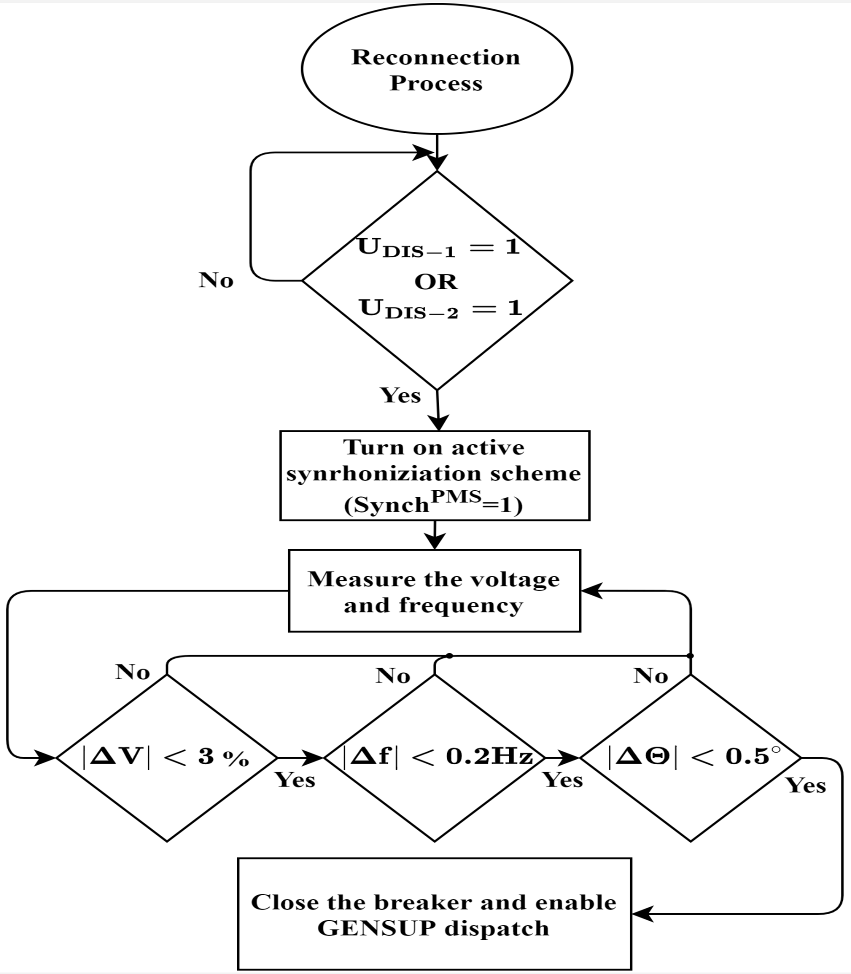
Energy reserve to prolong the system operation

Maintain adequate reserve

PMS: PLANNED ISLANDING PROCESS



PMS: RECONNECTION PROCESS



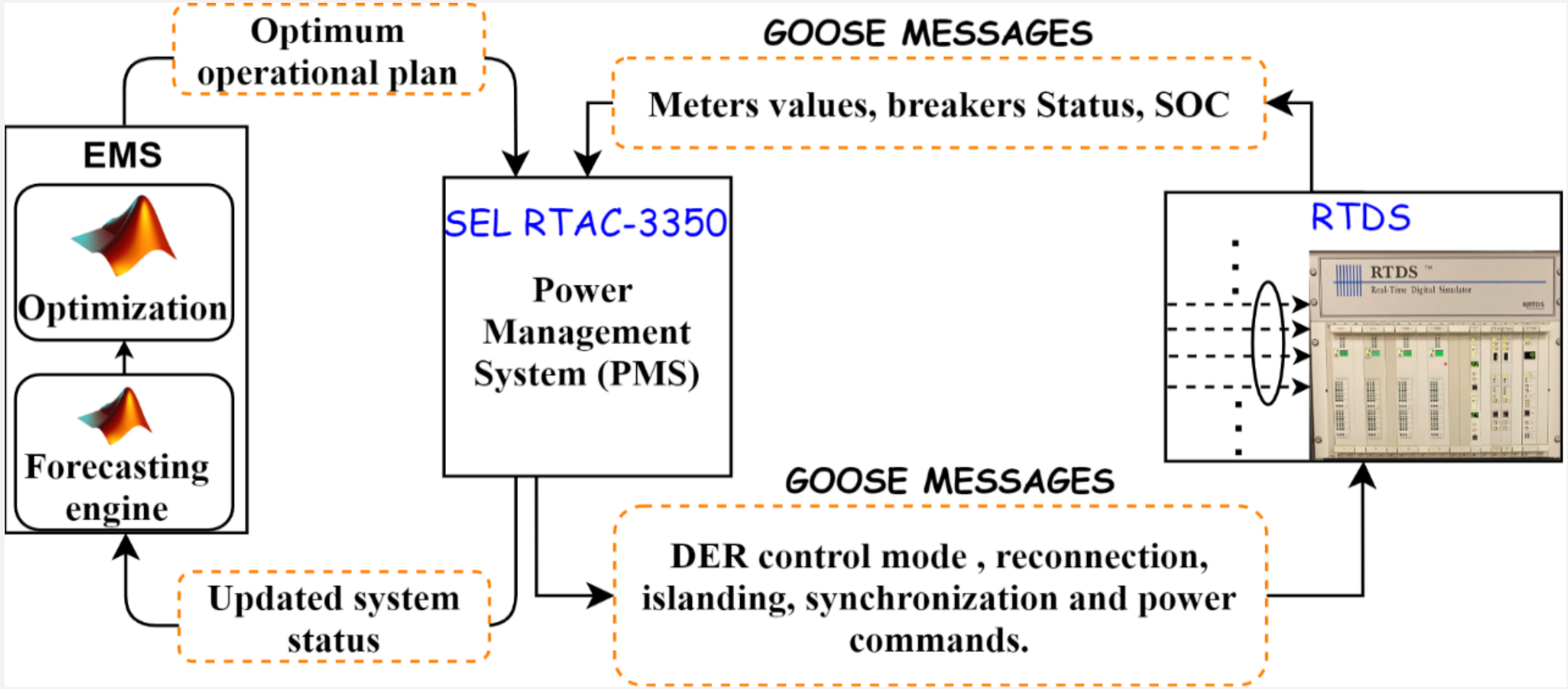
PMS: UNPLANNED ISLANDING

- Unintentional islanding events are detected by inspecting the status of diesel plant breakers.
- Upon unintentional islanding, the following is performed:
  - Shed non-critical loads (P_{Shed}) determined by (A) based on the load priority to avoid unnecessary load shedding.

$$P_{Shed} = P_{L+RGC} - (P_{PV} + P_{BESS}^{max}) \qquad (A)$$

  - Switch the BESS control to grid-forming.
  - Switch to islanded dispatch strategy.

HARDWARE IMPLEMENTATION

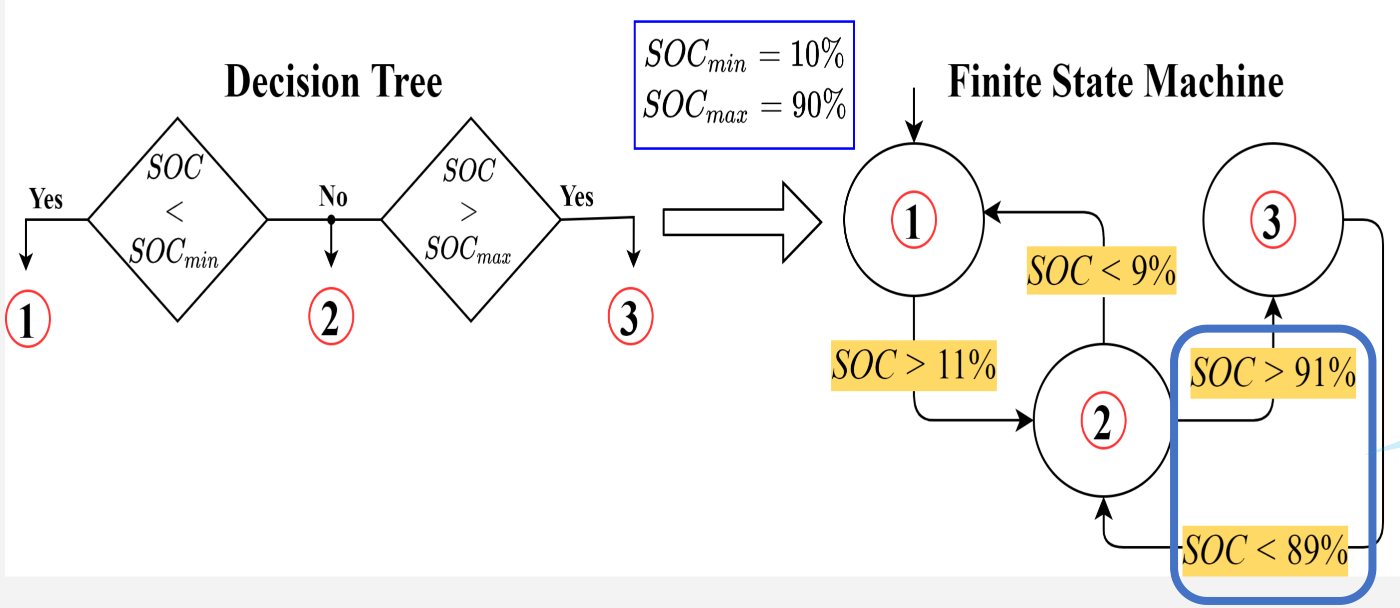


HARDWARE PROGRAMMING

- Finite State Machines (FSM) are a simple computational model that represents the logic design of many computer and automation applications.
- Employed in designing the sequential logic circuits of applications such as robots, vending machines and traffic lights.
- FSM based approach was used in implementing the PMS
  - Use of FSM makes it easy to assemble dead bands between the states, which prevents frequent switching between different cases.

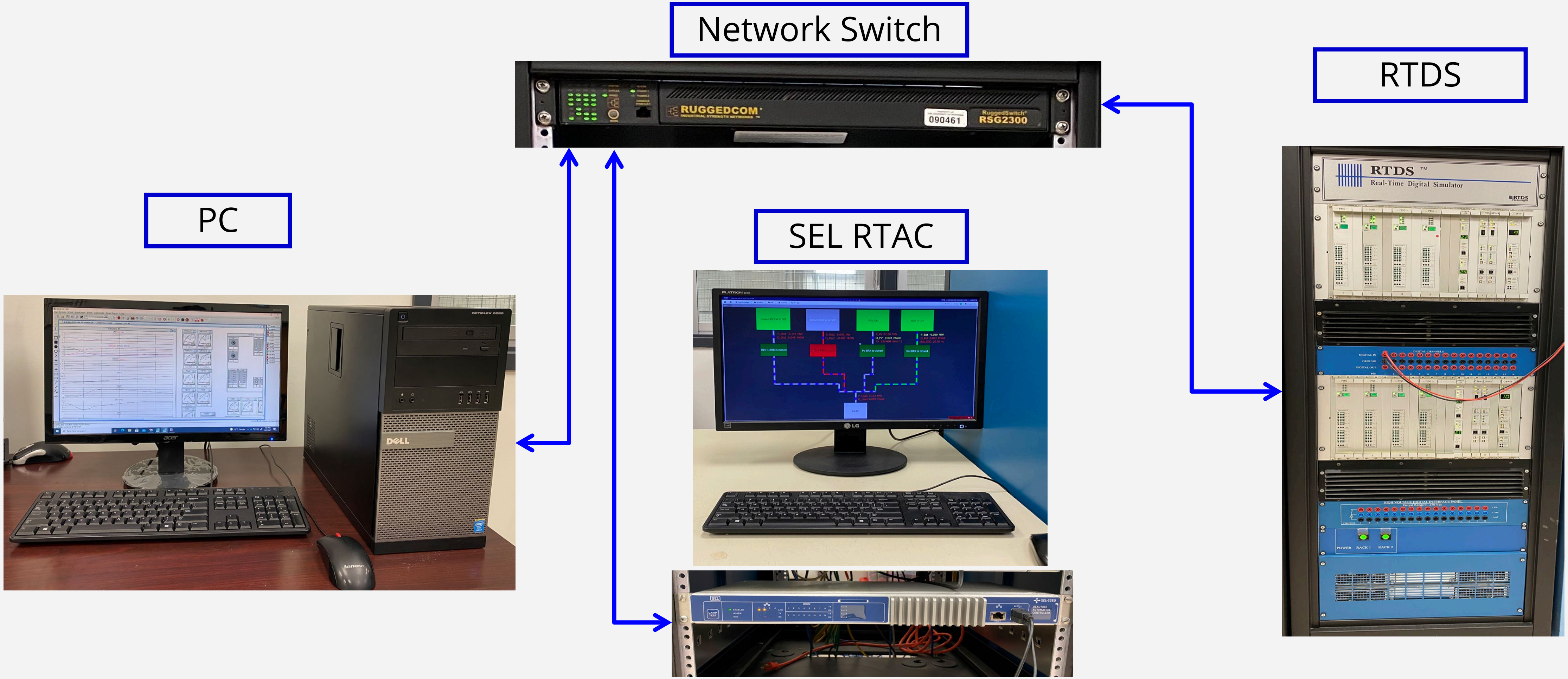
HARDWARE PROGRAMMING

Decision tree to FSM conversion

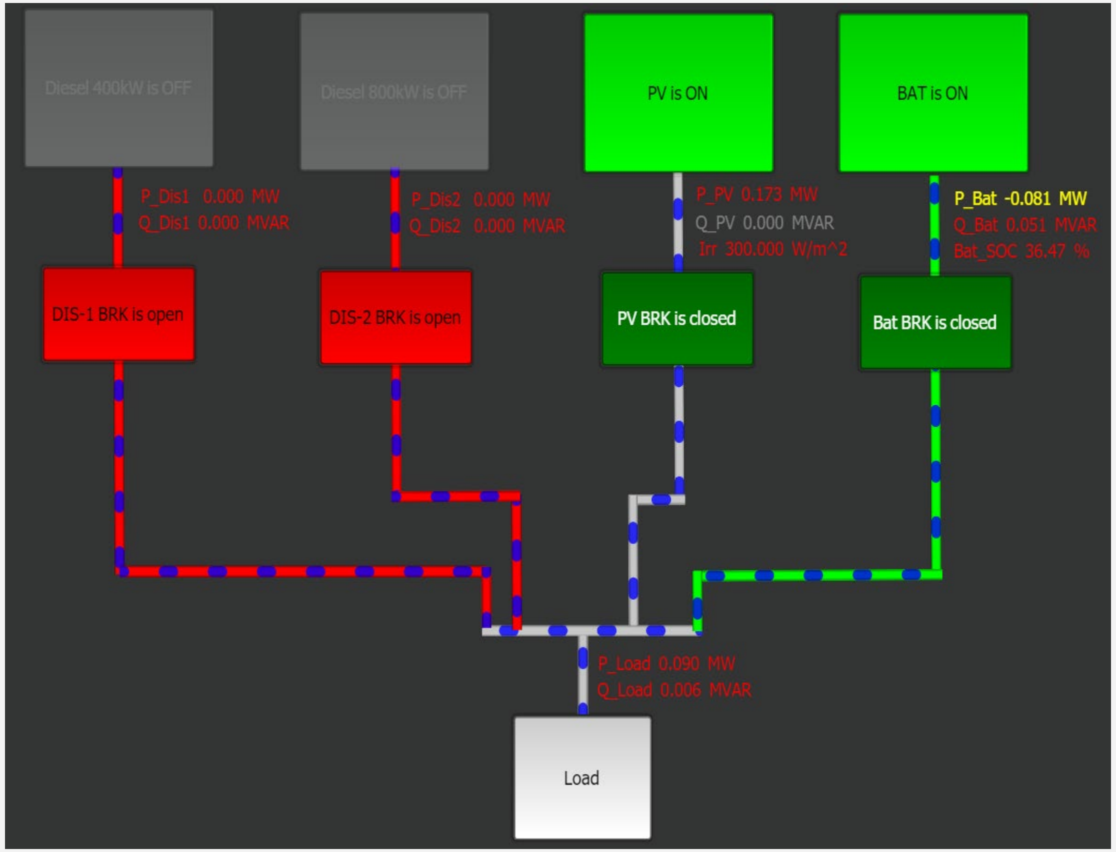


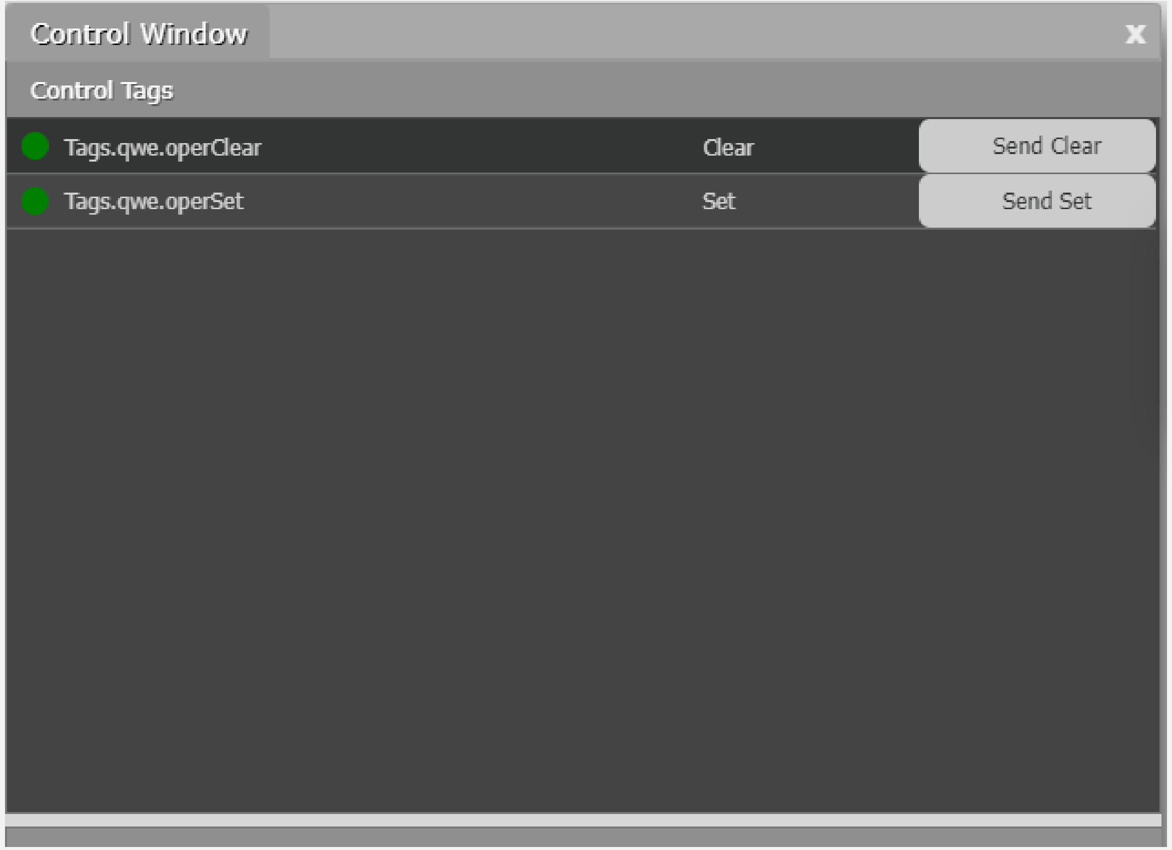
1% deadband

LABORATORY SETUP

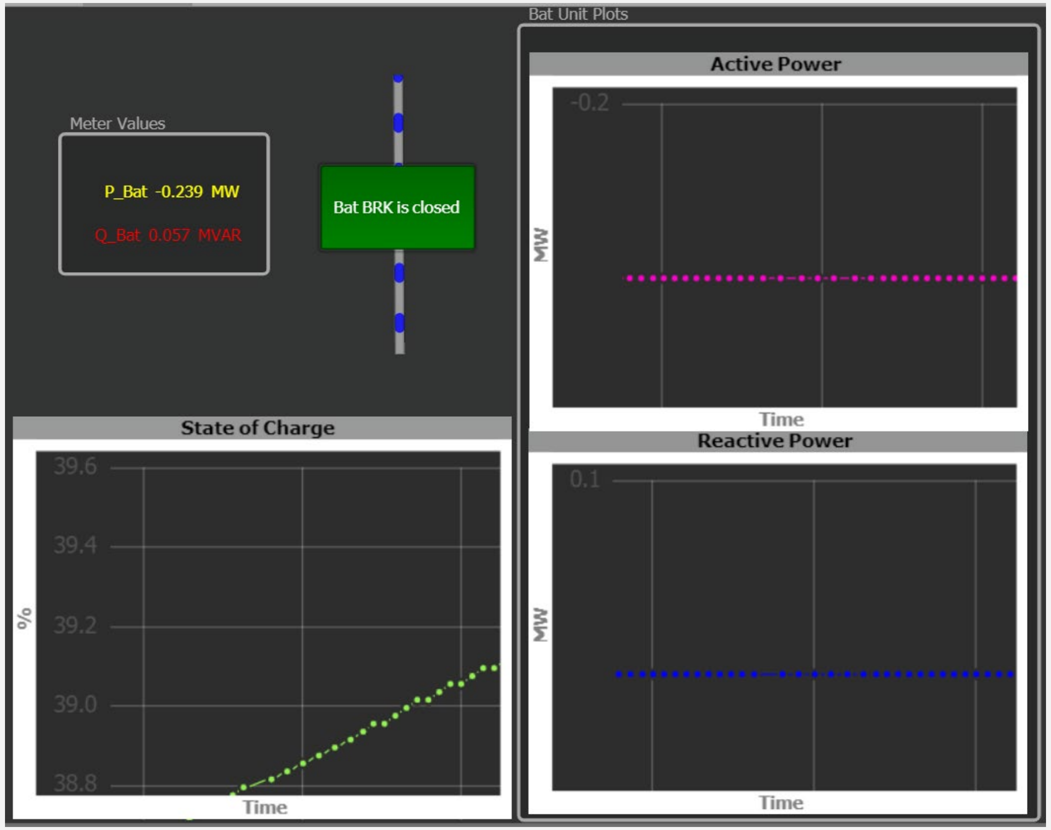


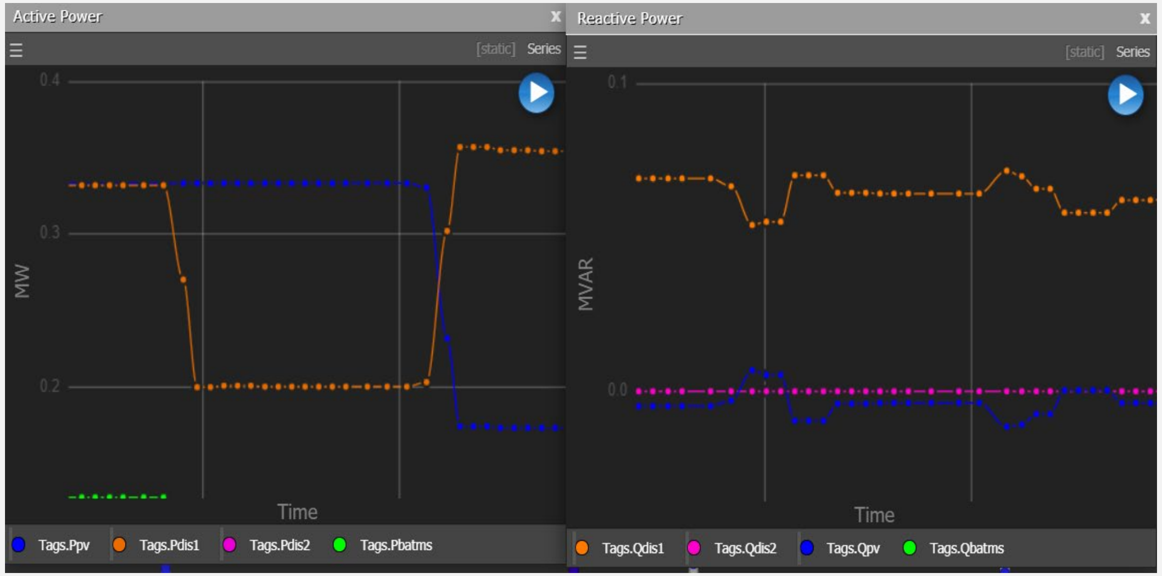
HUMAN MACHINE INTERFACE





HUMAN MACHINE INTERFACE





RESULTS

- The developed CHIL-based testbed was used to demonstrate the applicability of the hierarchical controller to implement energy management over a 24-hour control horizon.

Optimum operational plan

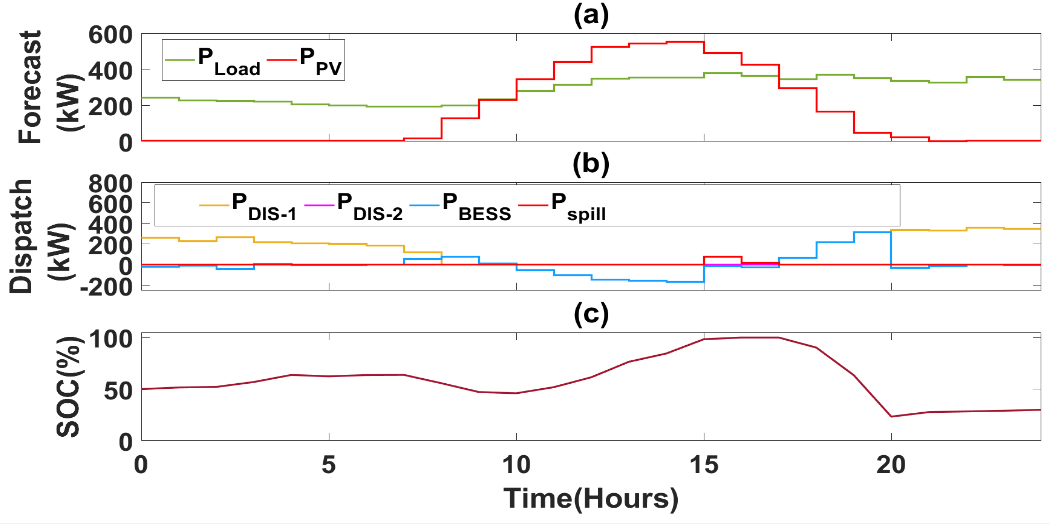


Fig. 20: Optimum operational routine: (a) Forecasts, (b) Dispatch, and (c) SOC

System actual operation

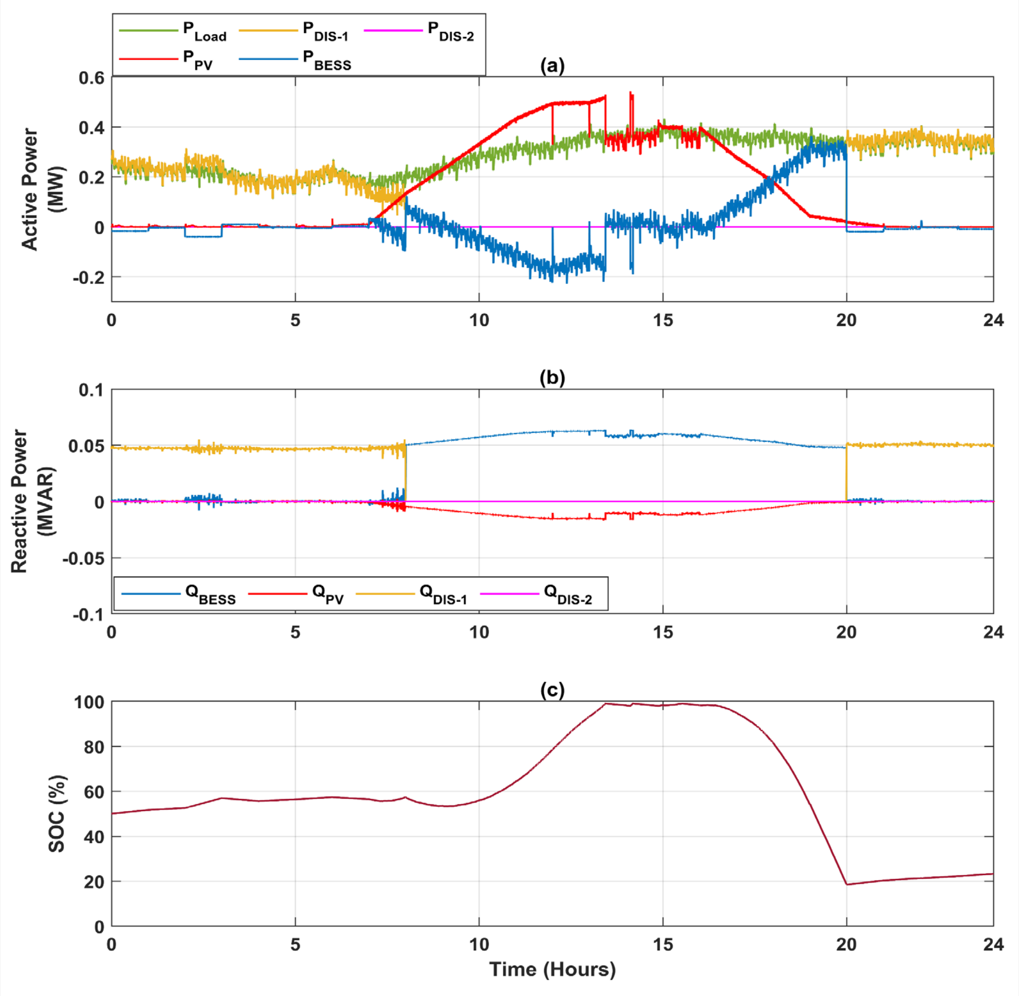


Fig. 21: System actual operation: (a) active power, (b) reactive power, (c) spilled power, (d) SOC

RESULTS

Diesel minimum loading scenario (8th hour)

DIS-1 (400 kW)
Min load = 0.12 MW

Secondary control modifies BESS power level

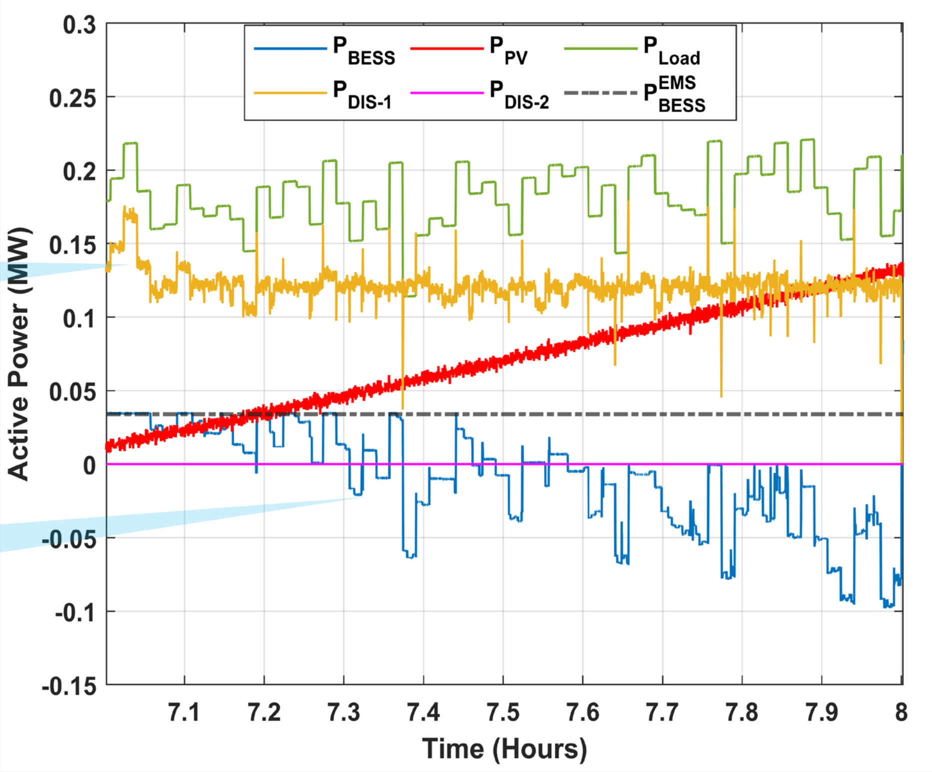


Fig. 22: Diesel minimum loading scenario (8th hour): Active power

RESULTS

DIS-1 overloading scenario (23rd hour)

DIS-1 (400 kW) Over-loading

Battery discharges at higher power

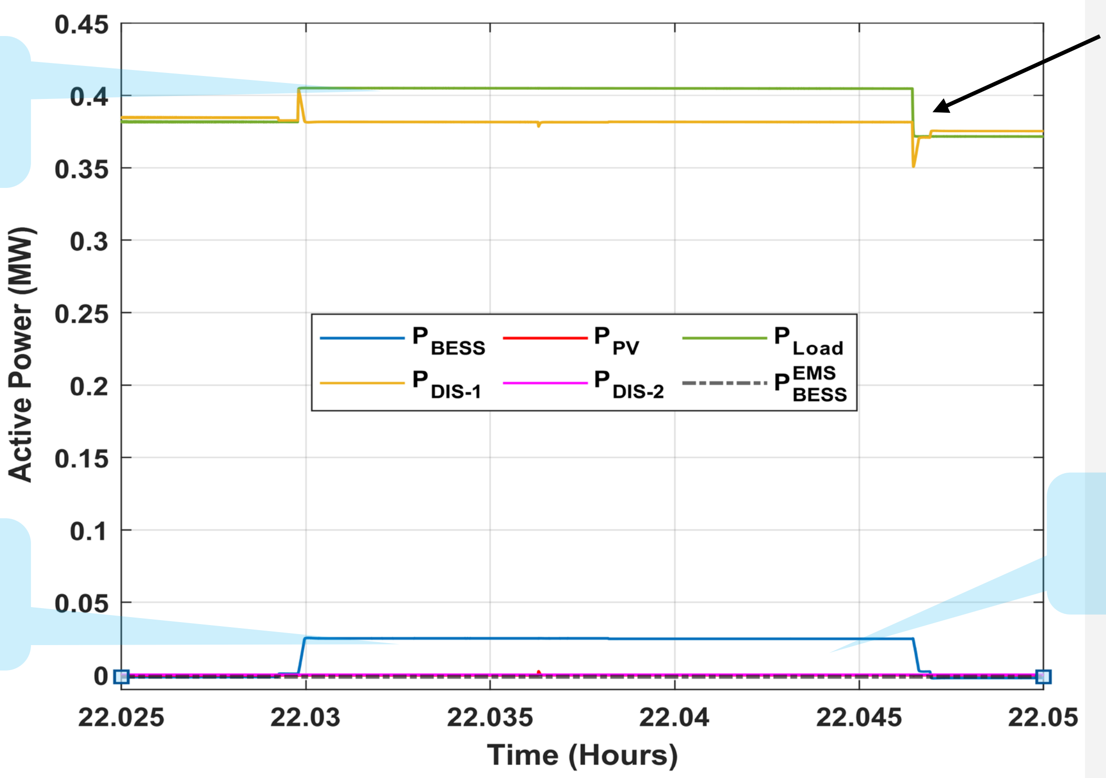


Fig. 23: DIS-1 overloading scenario (22nd hour): Active power

Load drop

Battery follows the EMS signal

RESULTS

Results from 15th hour, when SOC reaches SOC_{MAX}

PV system starts tracking the load

SOC hits its maximum

PV : MPPT

PV : Limited-power

BESS charges

SOC reaches the lower band setpoint

SOC reaches the 99%

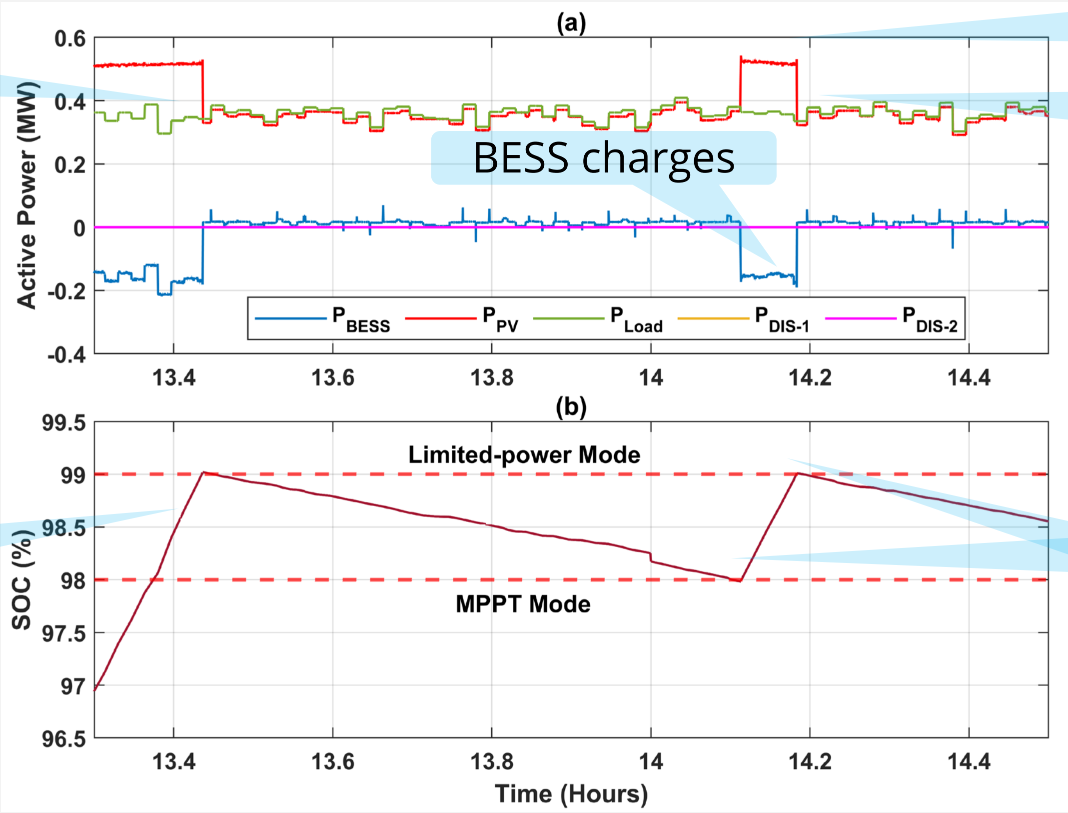


Fig. 24: Results from 15[th] hour, when SOC reaches SOC_{MAX}: (a) active power and (b) SOC

RESULTS

Increase P and Q of BESS to unload DIS-1

Planned islanding at the start of 9th hour

Voltage and frequency within certain limits

- Diesel disconnection
- Battery forming the grid

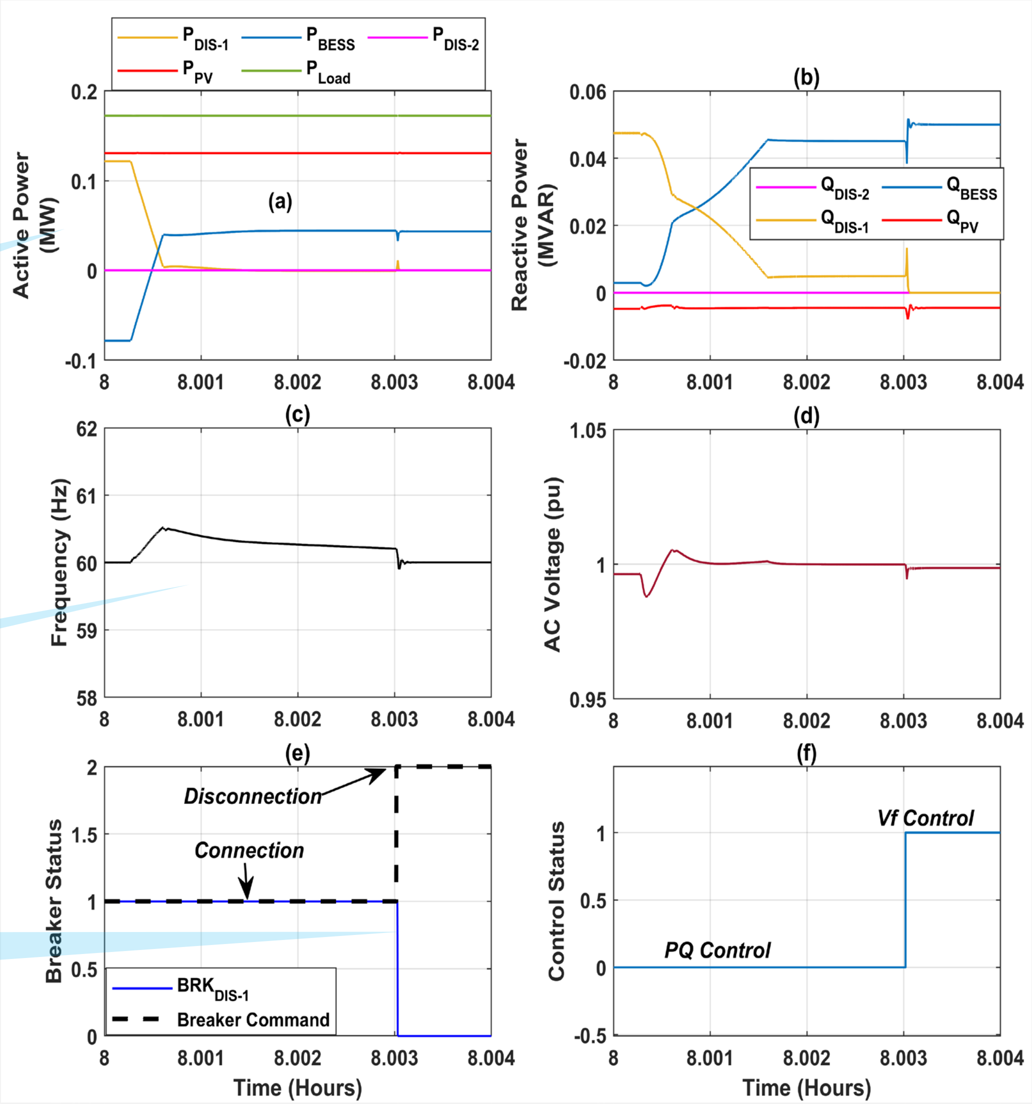


Fig. 25: Planned islanding at the start of 9th hour: (a) active power, (b) reactive power, (c) frequency, (d) AC voltage, (e) diesel unit breaker status, and (f) battery control mode

RESULTS

Battery follows EMS signal

Reconnection at the start of 21st hour

Activate synchronization scheme

Battery in grid-following mode

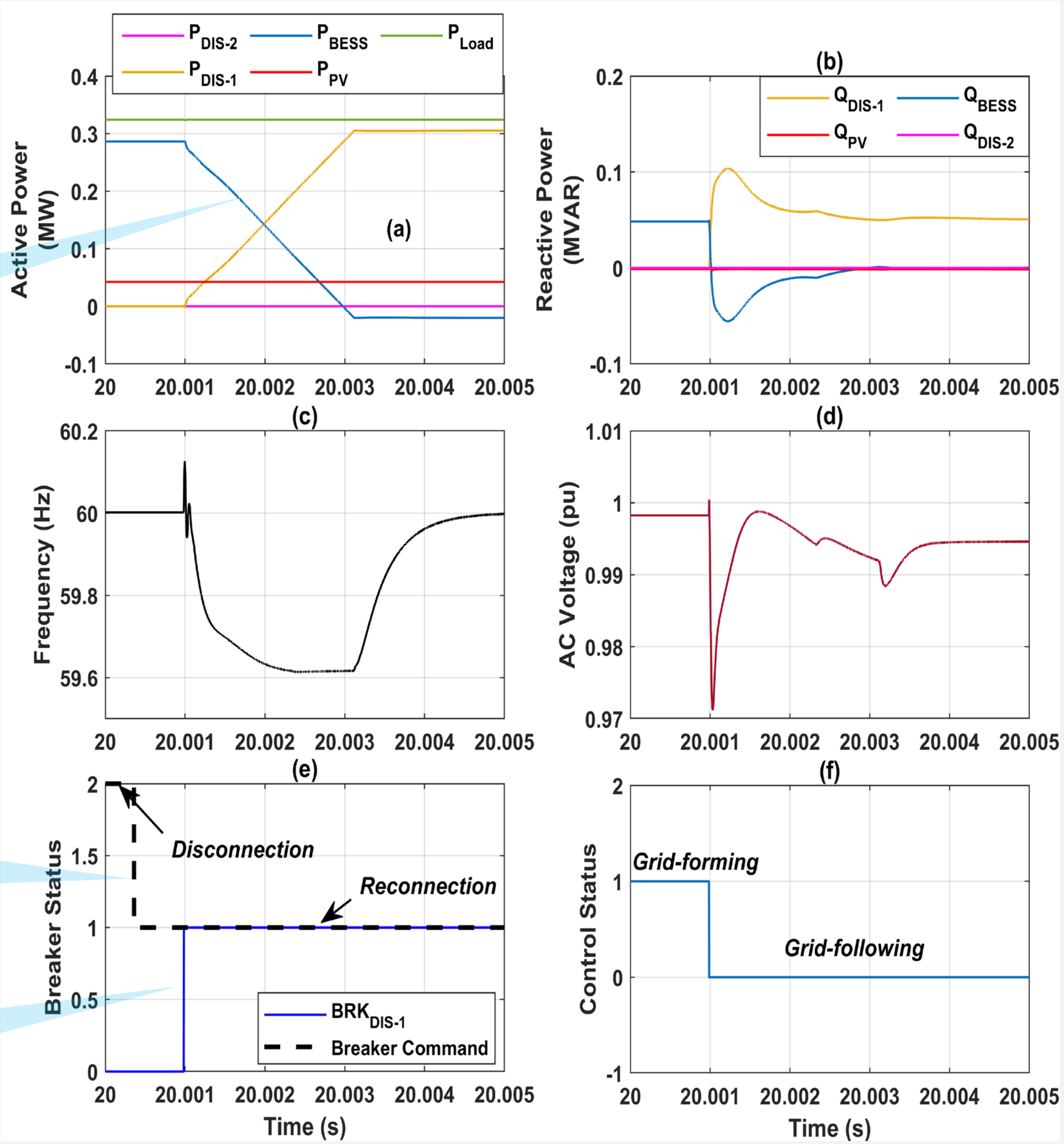


Fig. 26: Reconnection at the start of 21st hour: (a) active power, (b) reactive power, (c) frequency, (d) AC voltage, (e) diesel unit breaker status, and (f) battery control mode

CONCLUSIONS

- A power management system was designed for an off-grid power system PV, Diesel generation, and BES, and implemented on a SEL RTAC 3350 hardware.
- PMS could successfully navigate along the power dispatch schedule provided by the EMS while adapting to the limitations of the units to attain stable microgrid operation.
- CHIL simulation setup implemented using RTDS® real-time simulator provided highly flexible environment to test the functionality of the power management system.
  - Setting up of IEC 61850 GOOSE message-based communication between RTDS and SEL RTAC unit was expedient.
  - The competence of the IEC 61850 GOOSE communication to facilitate the interaction between the PMS and the microgrid components was validated.

ACKNOWLEDGMENTS

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THANK YOU