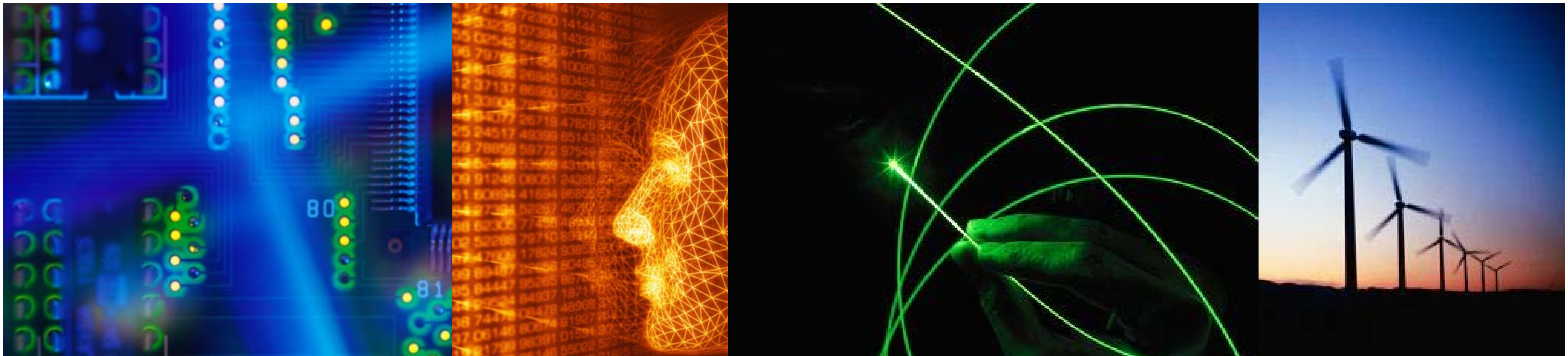

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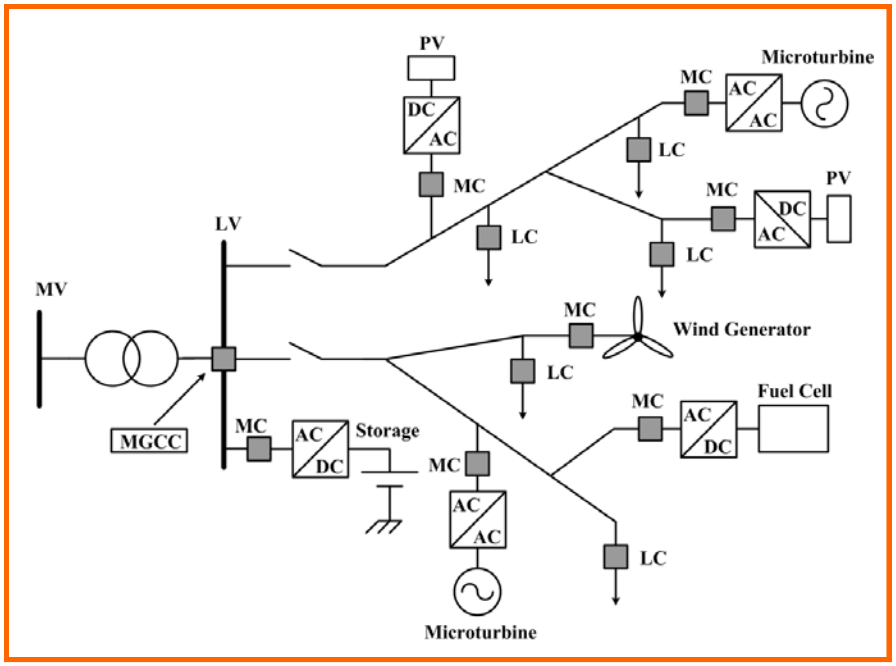
Use of Microgrids and DERs for black start and islanding operation

João A. Peças Lopes, FIEEE

May 14-17, 2017 - Wiesloch

The MicroGrid Concept

- A Low Voltage distribution system with small modular generation units providing power and heat to local loads
- A local communication infrastructure
- A hierarchical management and control system:
  - MicroGrid Central Controller (MGCC)
  - Local Load Controller (LC)
  - Local Microsource Controller (MC)

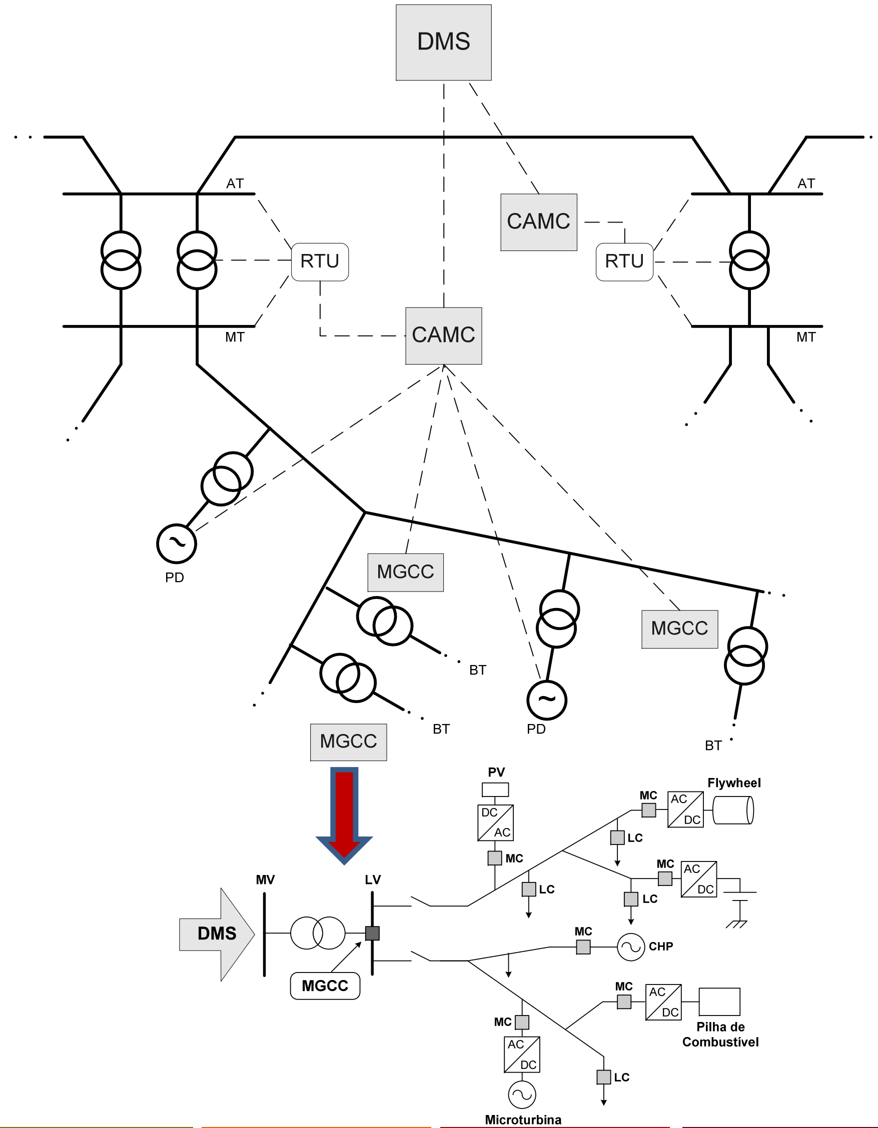


Operation Modes:

1. **Normal Interconnected Mode**
2. **Emergency Mode: Autonomous Operation**
   - **Intentional Islanding**
   - **Forced Islanding**

MV networks of the future – Muti-Microgrids with DER

- Concept of Multi-Microgrid
  - An evolution from the MG concept;
  - MV network;
  - Larger geographic dimension;
  - Topological diversity;
  - Very large number of active players;
  - Developed over a large communication infrastructure.



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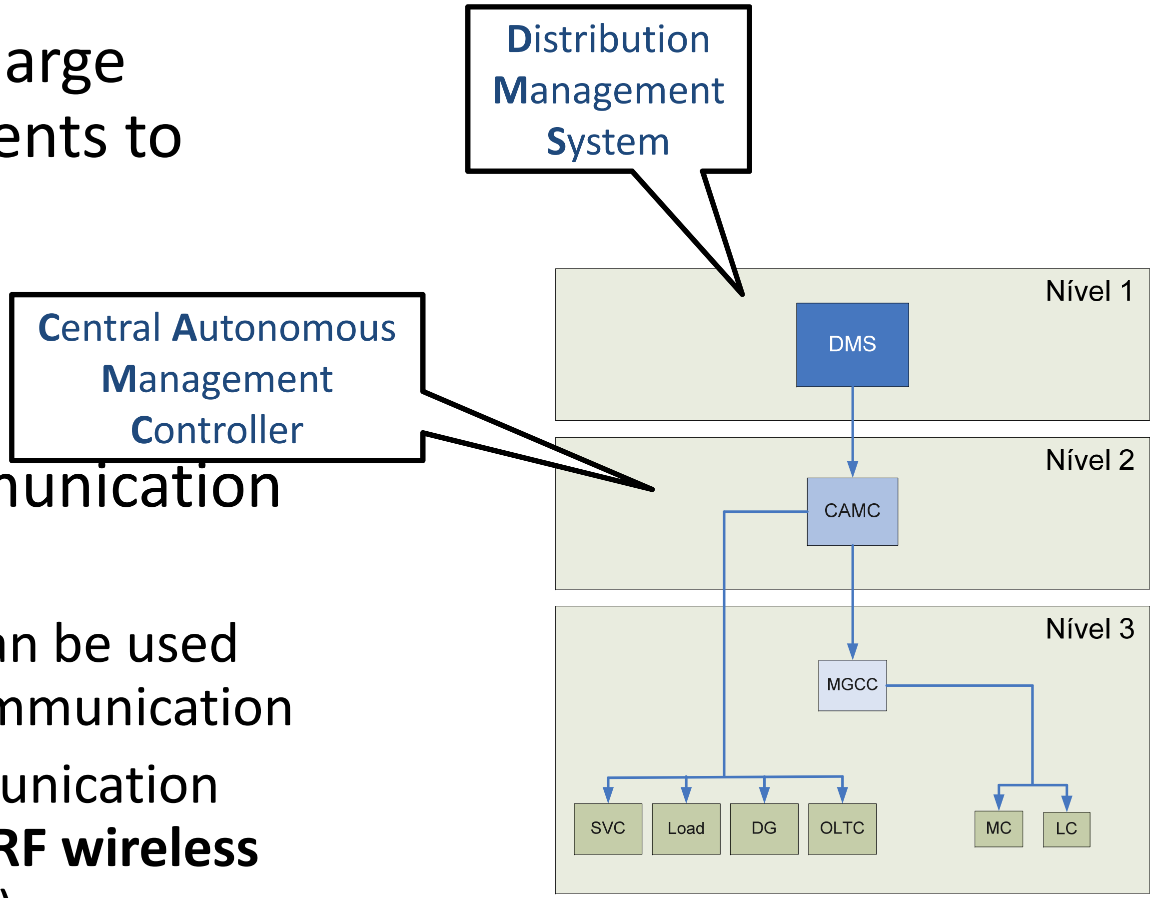
Control Structure of the Distribution Grid

- Hierarchy of Control
  - Imposed by the large number of elements to control;
  - Requires a communication infrastructure
    - Smart meters can be used as nodes for communication
    - Last-mile communication protocols (PLC, **RF wireless Mesh networks**)



An Overview on MG Operation and Control Issues - 1

- **MicroGrids are inverter dominated Grids:**
  - New issues are introduced in terms of operation and control in comparison with conventional power systems comprising synchronous generators

- **MG are systems with very low global inertia and comprise MS with slow response:**
  - During MG islanding operation, load-tracking problems arise since microturbines and fuel cells have slow response to control signals and are inertia-less
  - A system with clusters of MS designed to operate in islanded mode requires some form of energy buffering to ensure initial energy balance
  - The active power shortage caused in the MG when moving to islanding operation or due to load or power variation during islanding operation mode must be compensated by energy storage devices

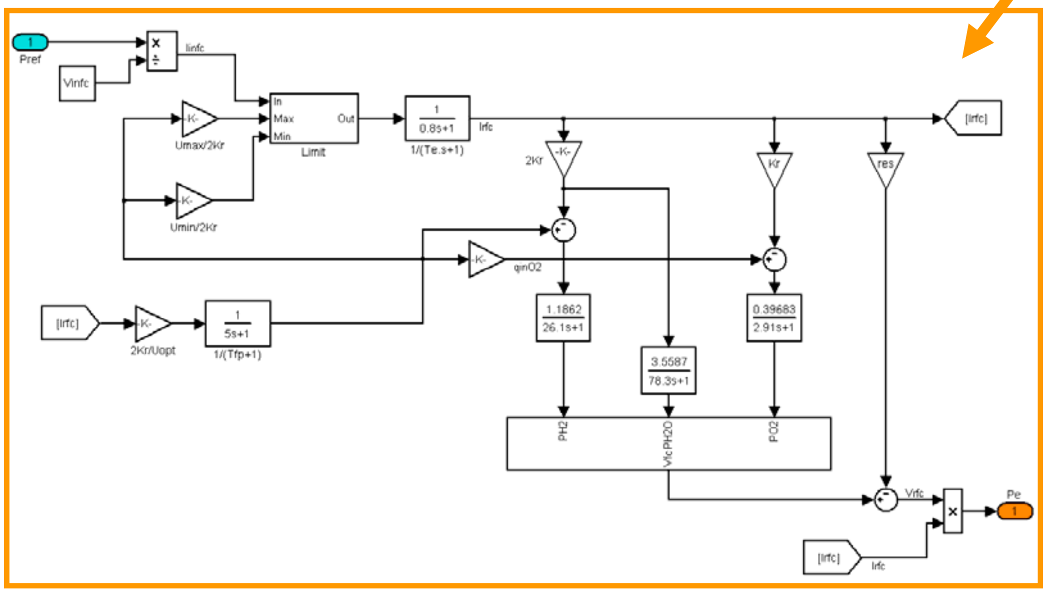
An Overview on MG Operation and Control Issues - 2

- Moving to islanding operation (forced islanding):
  - When the MG transfers to island operation, an immediate change in the output power control of the MS is required: MS operation mode change from a dispatched power mode to one controlling frequency of the islanded section of the network
  - The control strategy to be adopted has to combine the frequency control strategy with the storage devices response and load shedding possibilities, in a cooperative way to ensure successful overall operation, although acting independently at the MC and LC level
- MicroGrid Black Start:
  - If a system disturbance causes a general black out such that the MG is not able to separate and continue in islanding mode, and if the MV system is unable to restore operation in a predefined time, a first step in system recovery will be a local BS
  - The strategy to be followed will involve the MGCC and the local controllers
  - Use of predefined rules to be embedded in the MGCC software

MG Modeling – 1

MS Modeling

- A library of MS dynamic models was developed and implemented in *MatLab® Simulink®*



MicroSources:

Fuel-Cells
Microturbines
Wind Generators
Photovoltaic Generators

Storage Devices:

Flywheels
Batteries

Network Control and Management Systems

MG Modeling – 2

Inverter Modeling

- Main approaches for controlling power electronic interfaces :

- **PQ inverter control:**
  - Designed for grid-connected operation
  - The inverter is controlled to meet an active and reactive power set-point (the set-points are determined through specific algorithms or control functionalities)
  - In addition to active and reactive power flow control, this inverter is also responsible for the control of the DC-link voltage

- **Voltage Source Inverter (VSI) control:**
  - Designed for standalone operation (parallel operation with other VSI or with a stiff AC system is also possible)
  - The inverter "feeds" the load with pre-defined values for voltage and frequency
  - The VSI is used in order to interface a storage device (such a flywheel or a battery) with the AC grid. By making use of the energy stored in such devices, the VSI is able to emulate the behaviour of a synchronous machine, thus controlling voltage and frequency on the AC system

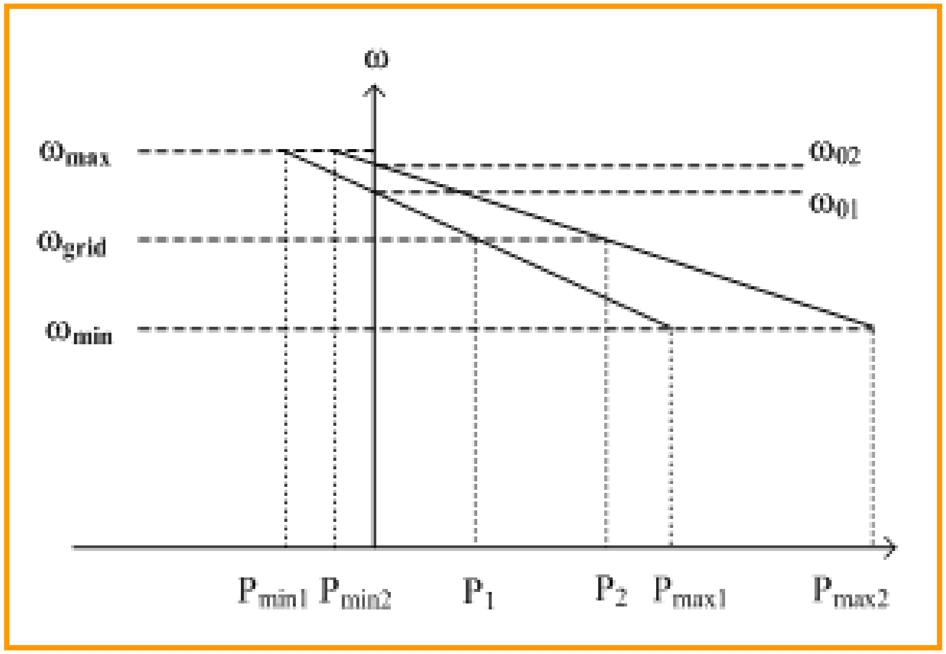
MG Modeling – 3

Inverter Modeling

- Voltage Source Inverter Control:
  - Frequency/active power and voltage/reactive power droop control concepts

$$w = w_0 - k_P \times P$$
$$V = V_0 - k_Q \times Q$$

$$w_{01} = w_{grid} + k_P \times P_1$$
$$V_{01} = V_{grid} + k_Q \times Q_1$$



MS Classification Regarding Control

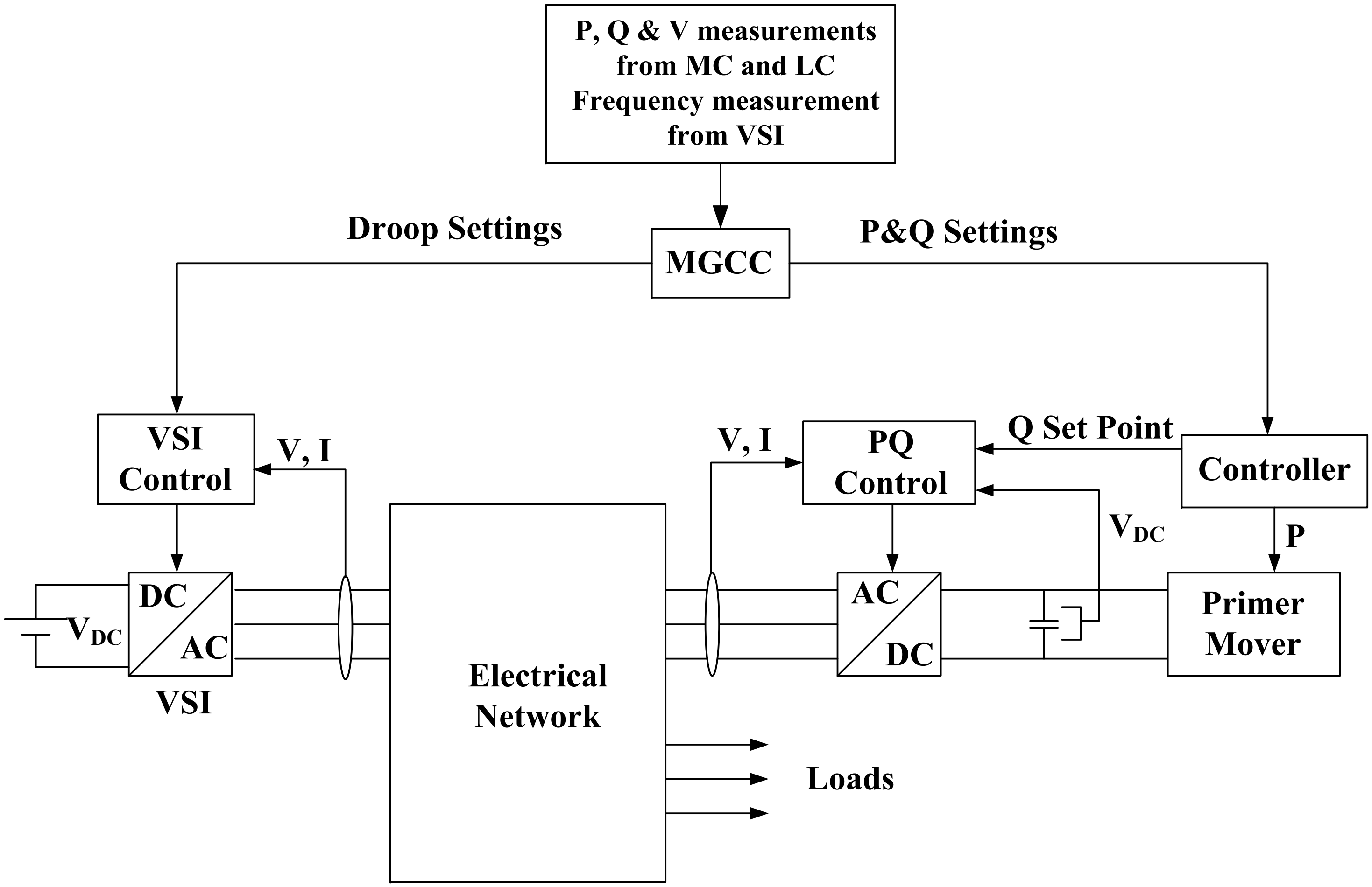
- Grid forming units: storage devices (coupled to VSI)
  - Definition of voltage and frequency in islanded systems
  - Power balance in islanded systems

- Grid supporting units: SSMT and SOFC
  - MS with capability of producing controllable active power on demand → can be used for MG active power secondary frequency control in islanded systems through the use of some form of dispatch

- Grid parallel units: PV and micro wind generator
  - Uncontrolled MS, injecting the maximum power extracted from the primary energy resource into the grid

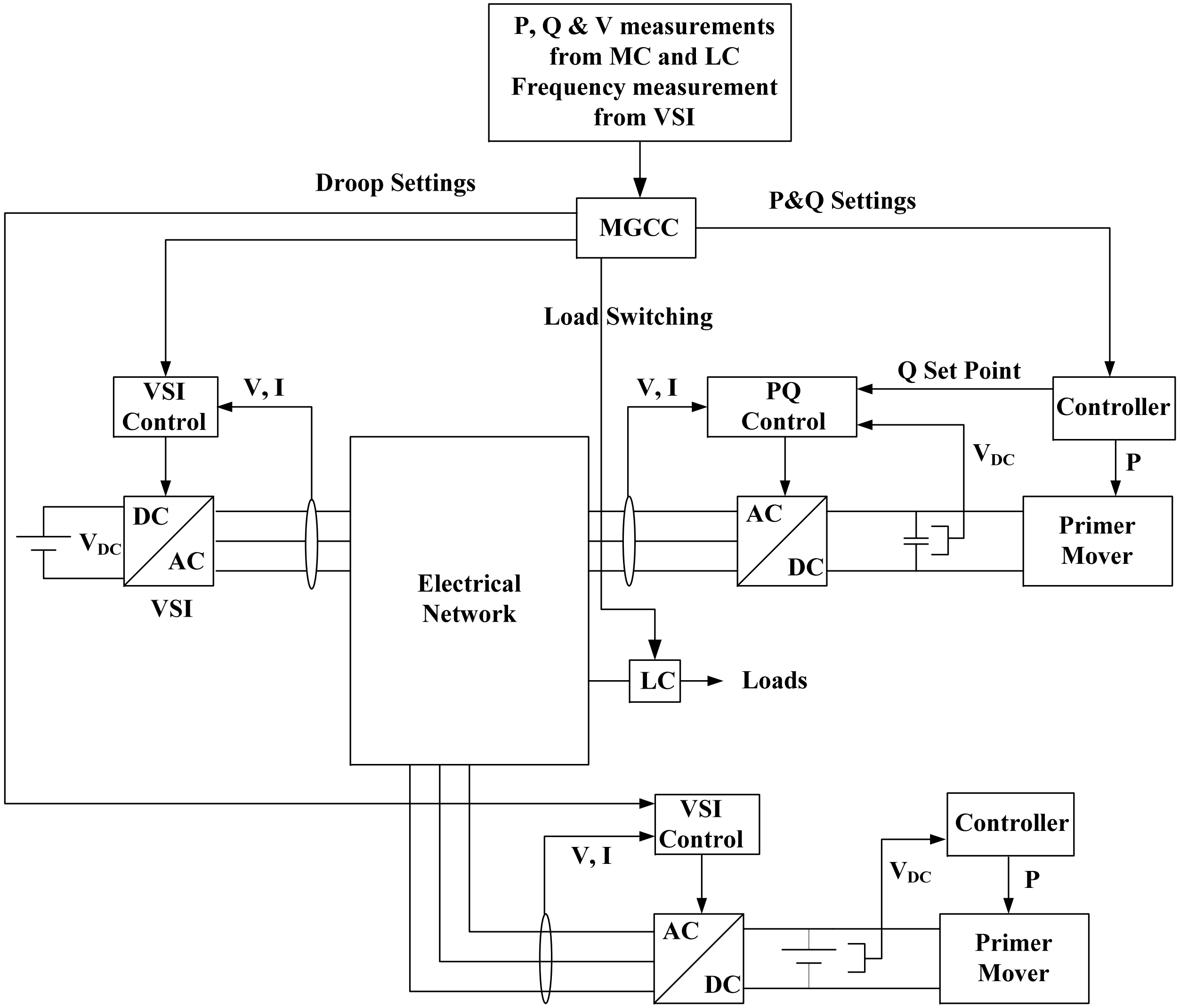
MG Control for Islanding Operation

Single Master Control Strategy



MG Control for Islanding Operation

Multi Master Control Strategy



MG Emergency Control Strategies - 1

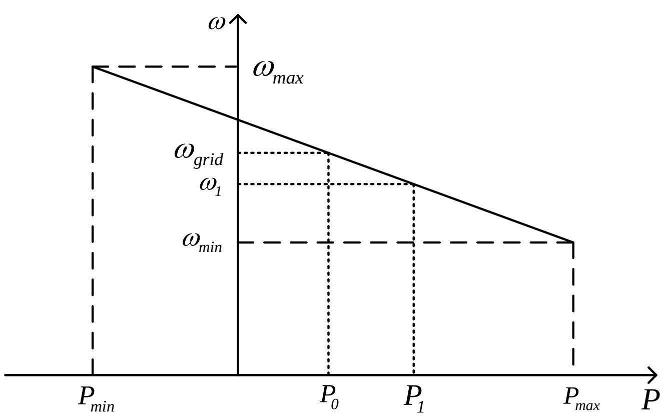
- Primary frequency control

  - VSI control principle makes it possible to react to system disturbances based only on information available at its terminals

  - MG operation does not rely on fast communications among MS controllers and the MGCC

  - Running in a larger time frame, a secondary control approach can be used to improve system performance

  - VSI active power output is proportional to the MG frequency deviation



VSI frequency decrease due to active power increase $\Delta P = P_1 - P_0$

MG Emergency Control Strategies - 2

- Load shedding:
  - Uses controllable/interruptible loads concept
  - To allow a fast response to the imbalance between load and generation
  - Emergency functionality to aid frequency restoration to its nominal value after MG islanding

Frequency Deviation	Load Shedding (%)
0.25	30
0.50	30
0.75	20
1.00	20

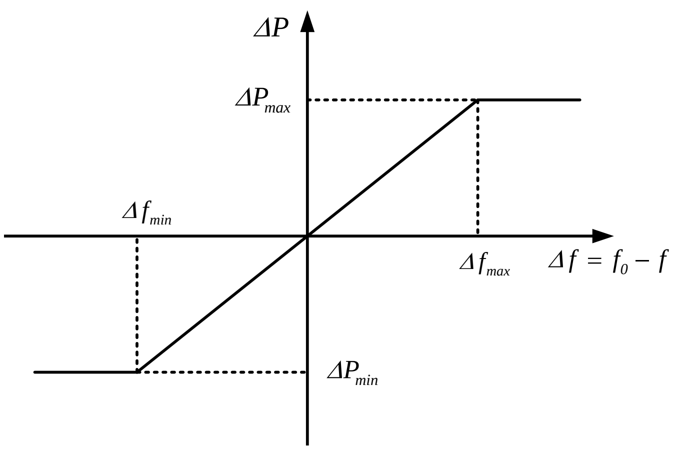
MG Emergency Control Strategies - 3

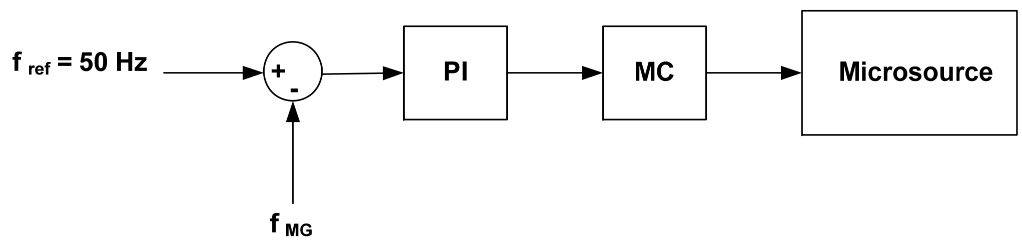
- Secondary frequency control:
  - During MG islanding operation, the frequency drifts from the nominal value following power or load variations

    ⬇

  - Power balance is assured by energy storage devices
  - If MG frequency stabilizes in a value different from the nominal one storage devices would keep on injecting or absorbing active power whenever the frequency deviation differs from zero.

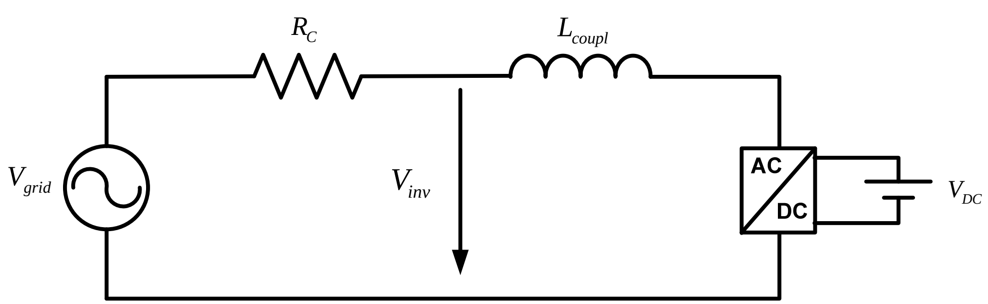
Correct permanent frequency deviations during islanding operation





MG Emergency Control Strategies - 4

- Voltage control:
  - In LV distribution grids, the resistive part is predominant over the inductive part
  - Active power flow is linked to voltage magnitude; reactive power flow is linked to the phase difference between bus voltages

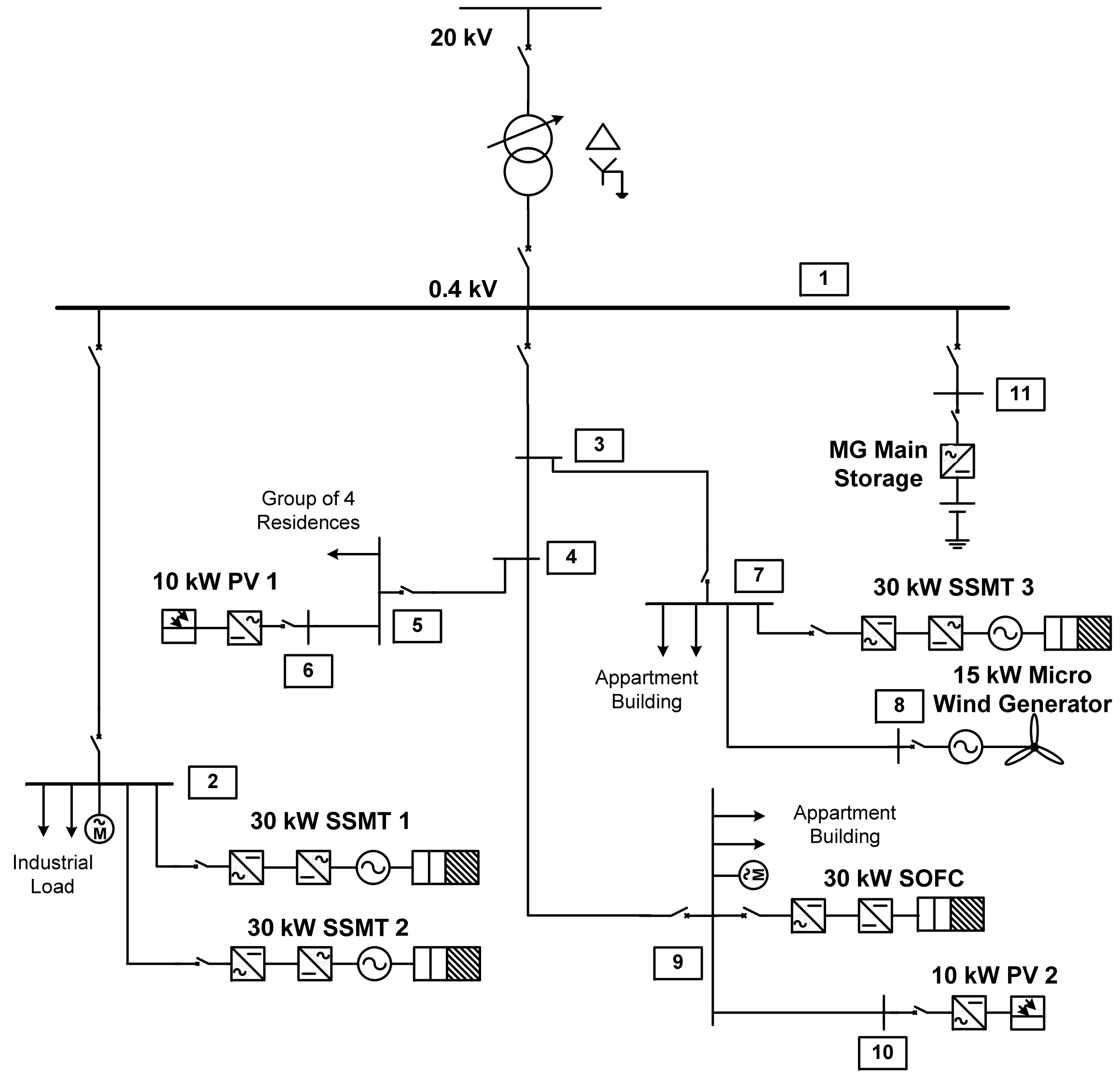


$$P_{inv} = \frac{V_{inv}^2}{R_C} - \frac{V_{inv}V_{grid}}{R_C}\cos(\delta)$$

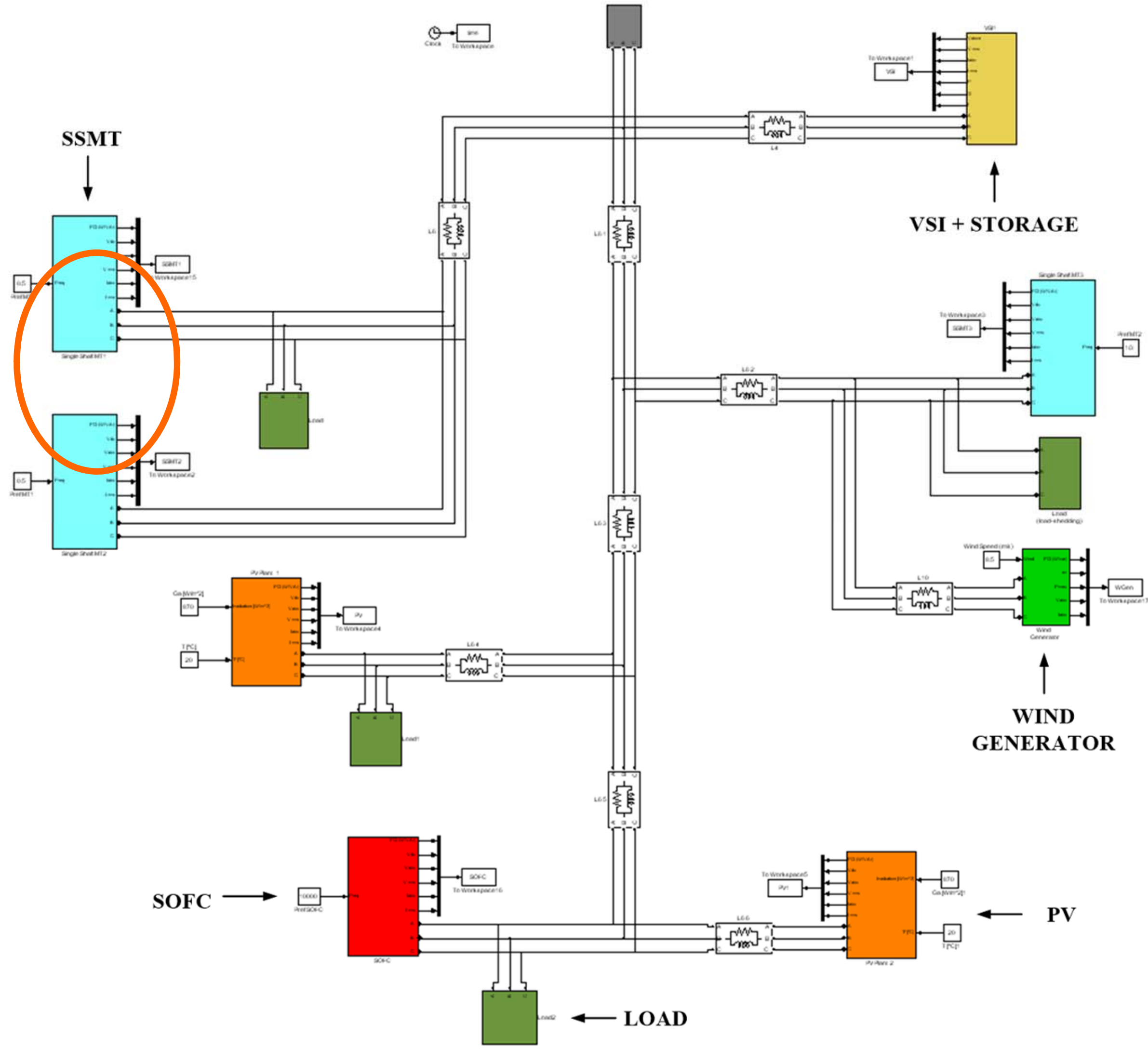
$$Q_{inv} = \frac{V_{inv}V_{grid}}{R_C}\sin(\delta)$$

- **Reactive power injection cannot be used for voltage control purposes**
  - VSI are used to control voltage in its connection point
  - PQ controlled inverters can be used for reactive power support
    - Power factor correction of the loads near the MS
    - Minimization of MG total losses

Dynamic Simulation of MicroGrids – Test System

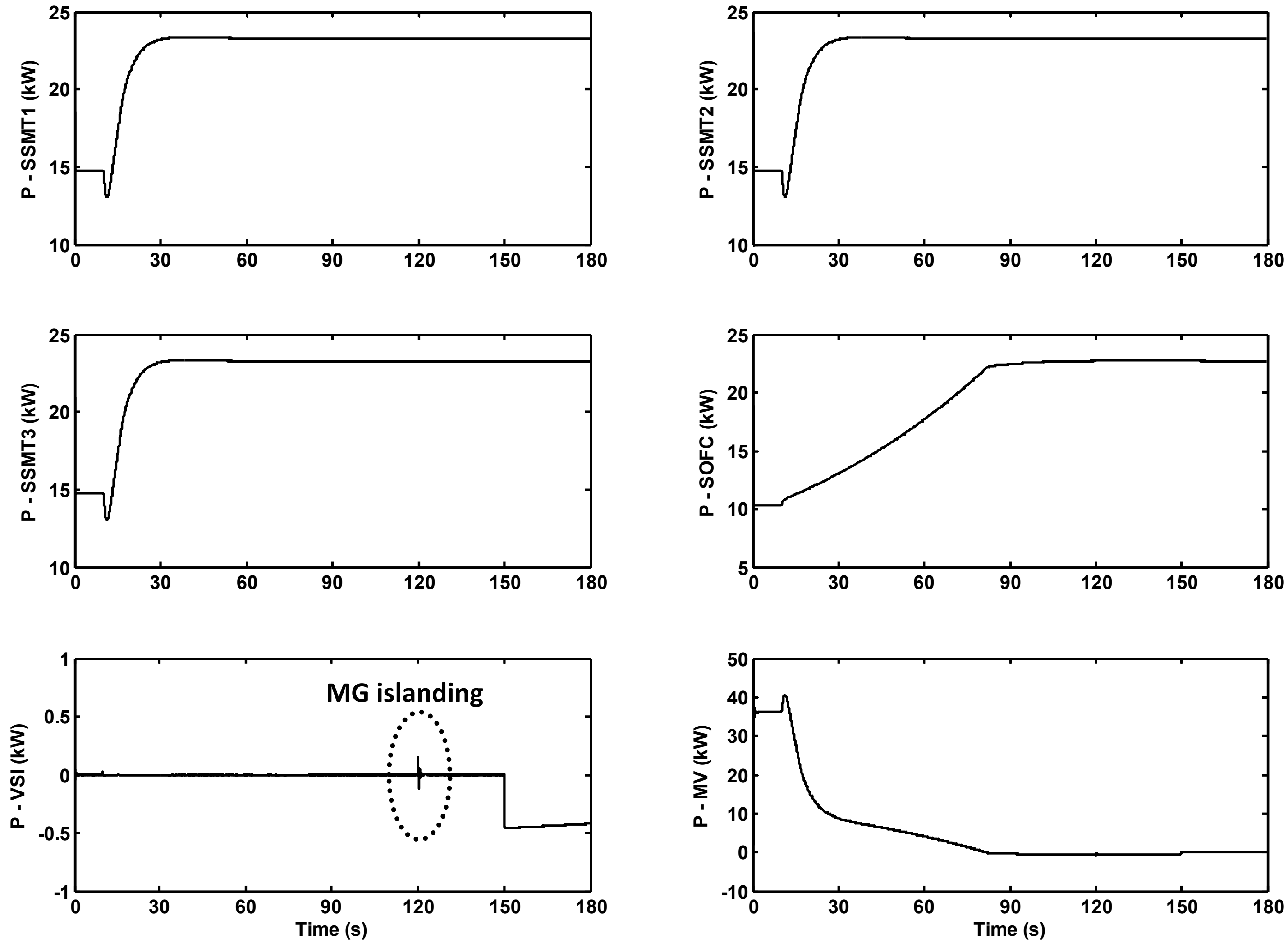


Dynamic Simulation of MicroGrids – Simulation Platform



Results from Simulations

MG Intentional Islanding



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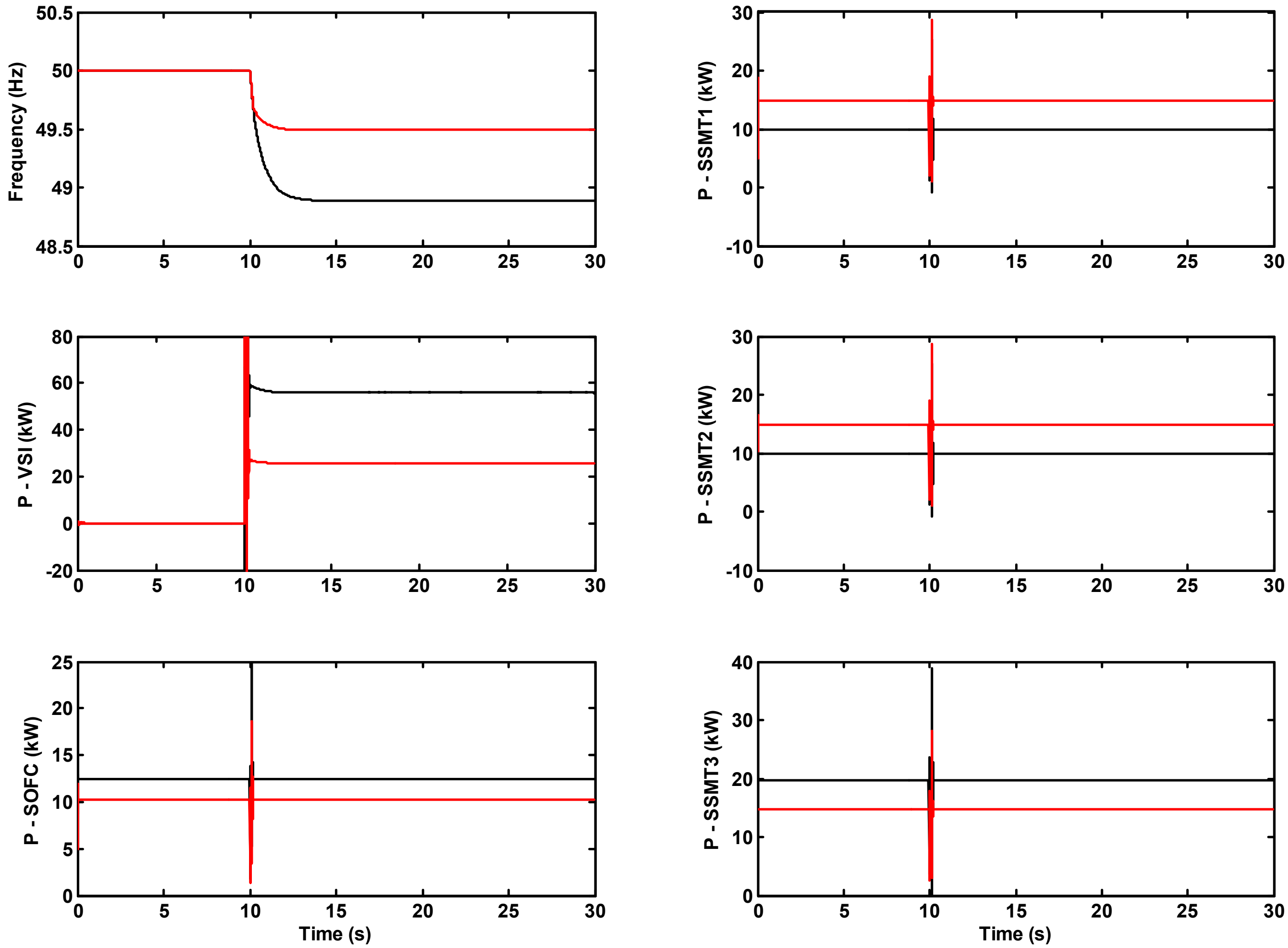
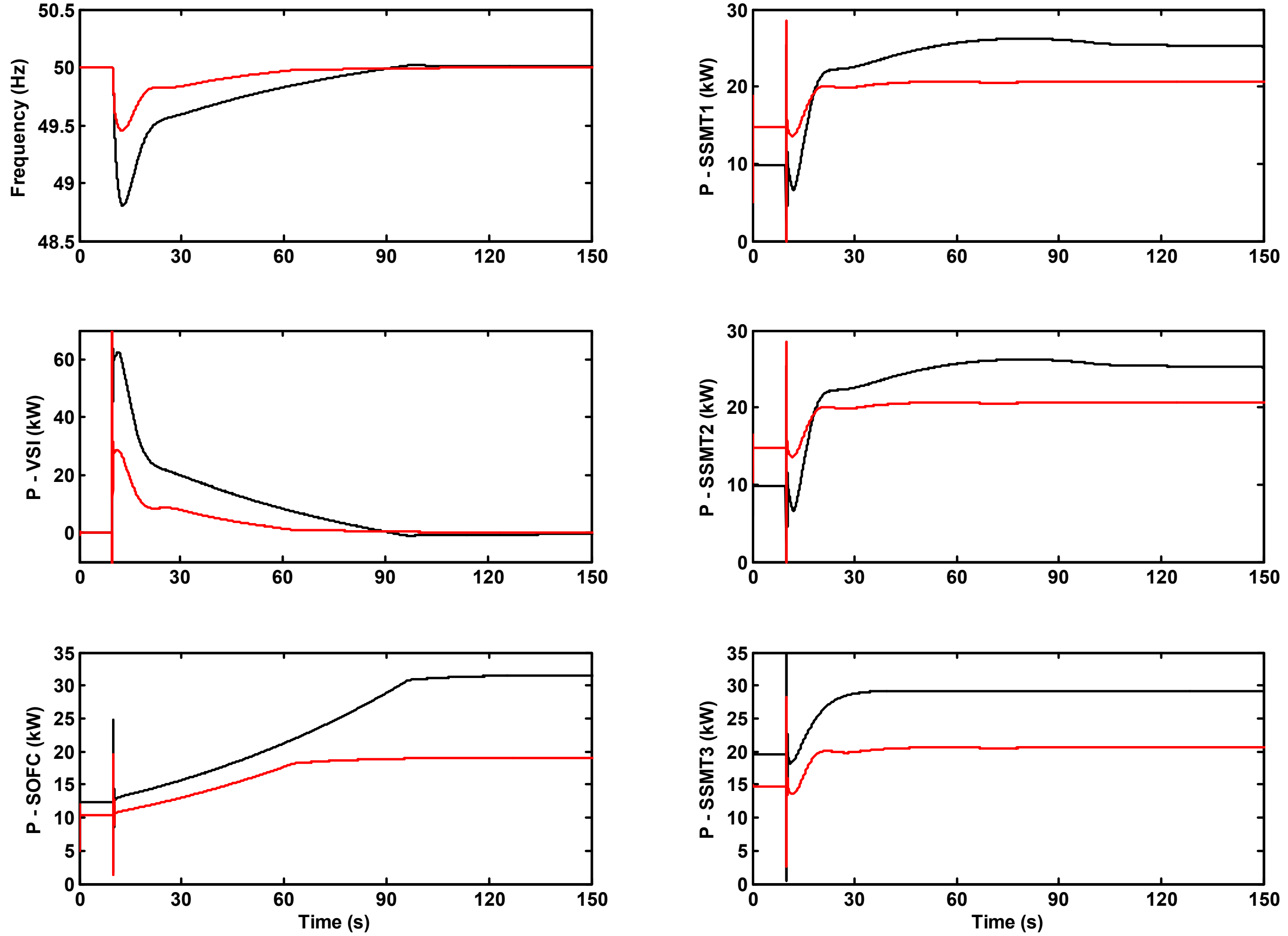
Results from Simulations

MG Forced Islanding – droop control



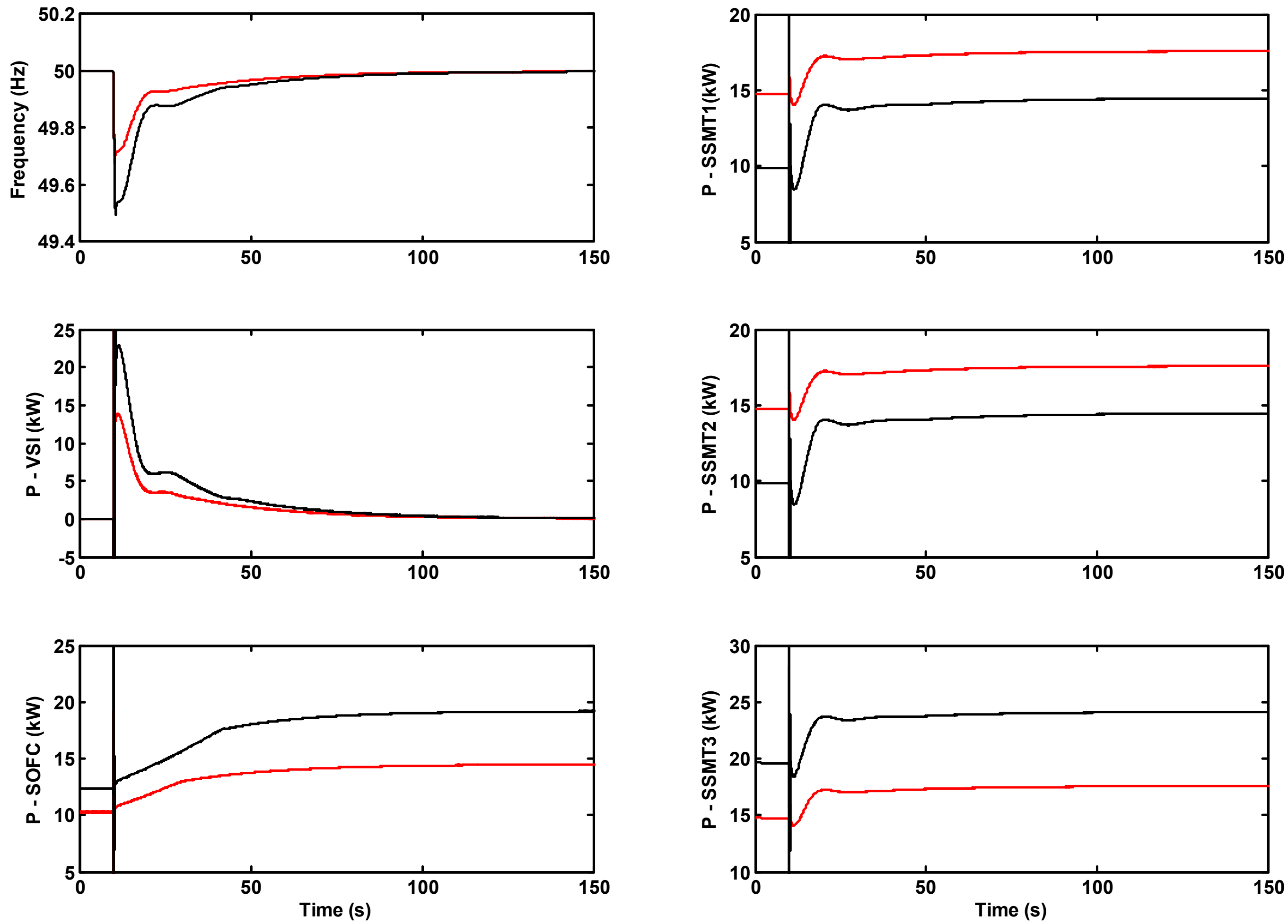
Results from Simulations

MG Forced Islanding – Secondary Frequency control



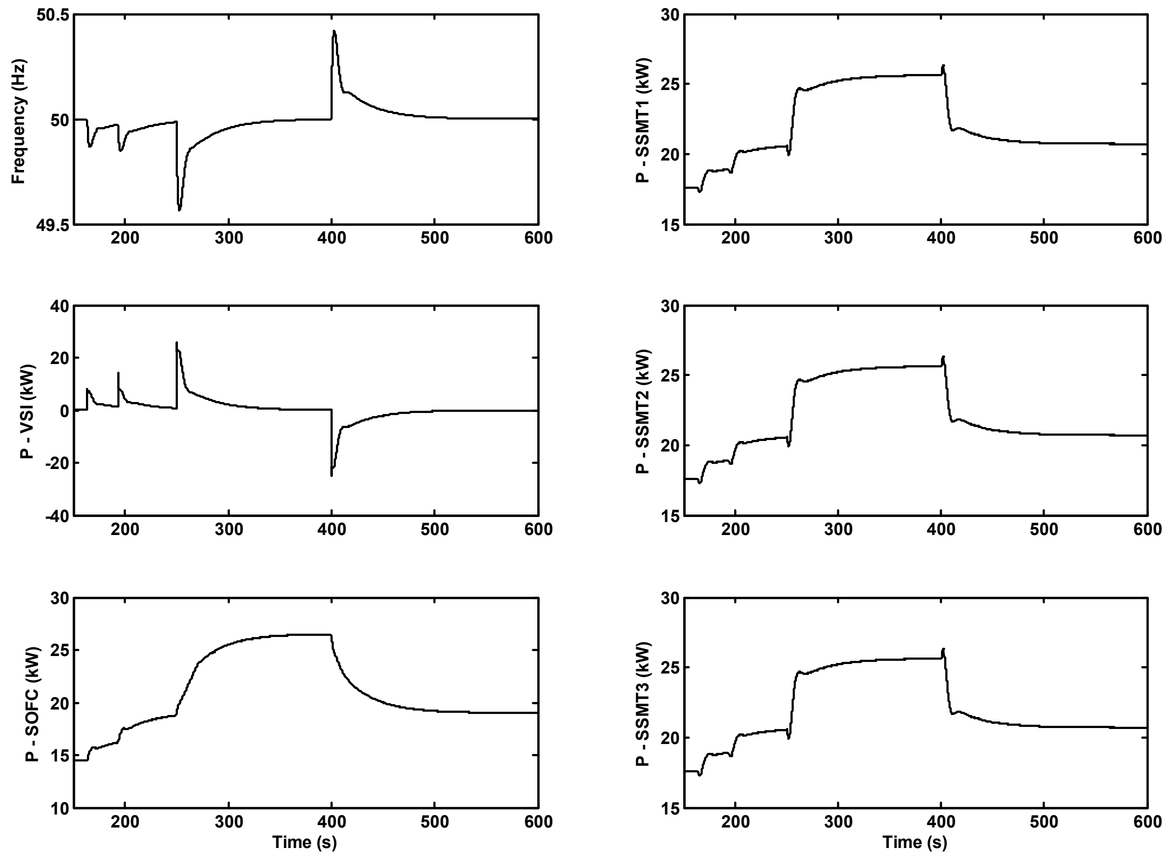
Results from Simulations

MG Forced Islanding – Secondary Frequency Control + Load Shedding



Results from Simulations

Load following during islanding operation



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MG Operation Issues

- Moving to islanding operation: How to achieve a seamless transition and ensure MG survival?

- Key Issues:

  - Is the energy available in storage devices enough for a seamless transition to islanded operation?

  - How much load must be shed?

These questions are related to MG frequency stability: MG ability to restore the balance between local load and generation in the moments subsequent to system islanding

Service Restauration– Main Steps
I – Using the MV Network – The MMG

- Energization of the MV Network and Synchronization of Islands:
  1. Switch off loads, separate transformers from the grid and disconnect reactive power sources.
  2. Create islands inside the MMG, around each micro-grid and around each generator with black start capability.
  3. Build the structure of the MV grid.
  4. Synchronization the several islands.
  5. Connection of priority loads.
  6. Energization by steps of the MV/LV transformers connecting micro-grids to MV network as well as with the remaining branches.
  7. Synchronization of the micro-grids with the MV network.
  8. Energization of the remaining MV/LV transformers.

- Restauration of Load and Reconnection of Generation:
  9. Restauration of load simultaneously with an increase of generation from controllable power sources, or alternatively by connecting non-controllable DG.
  10. Connection of non-controllable DG to the MV grid.
  11. Increase load taking into account the available generation capability.
  12. Activation of the AGC in the MMG. (This allows to assure the operation of the grid near the nominal frequency when in islanding conditions).
  13. Connection of the MMG to the NH grid upstream when this network becomes available.

II - Using Low Voltage MicroGrids for Service Restoration

- DG maturation can offer ancillary services, such as the provision of Black Start in Low Voltage grids

- Black-Start is a sequence of events controlled by a set of rules

  - A set of rules and conditions are identified in advance and embedded in MGCC software

  - These rules and conditions define a sequence of control actions to be carried out during the restoration stages

  - The electrical problems to be dealt with include:

    - Building LV network
    - Connecting MS
    - Connecting controllable loads
    - Controlling voltage and frequency
    - Synchronization with the MV network (when available)

MG Black Start – General Assumptions

- MS with Black Start capability:
  - Launch local generation autonomously
- Hierarchical control of the MicroGrid is used:
  - Load Controller (LC)
  - Microsource Controller (MC)
  - MG Central Controller (MGCC)
- MicroGrid has ability for:
  - Load and microsources disconnection after system collapse
  - Disconnection of the distribution transformer
  - Periodical records about MicroGrid status

MG Black Start – Sequence of Actions

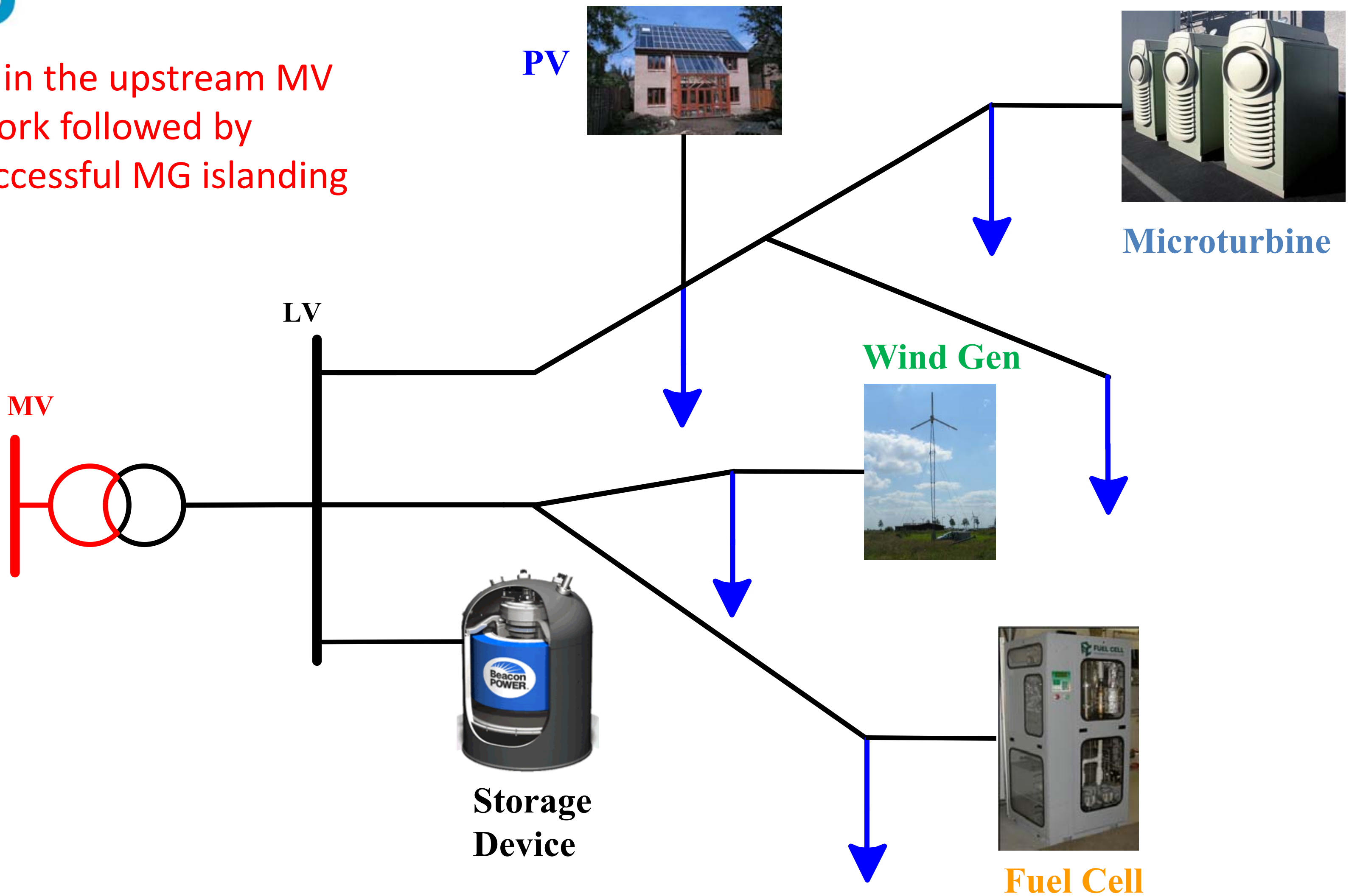
- Multi Master Operation in the initial stages of the procedure
- Disconnect all loads and sectionalize the MG so that some microsources may feed its own loads – Creation of small islands inside of the MG
- Start energizing the LV cables and the distribution transformer (using the storage device)
- Synchronize the other microsources with the LV network
- Connect controllable loads taking into account the available storage capability (including motor load start-up)
- Connect non-controllable microsources or those without black start capability to get crank power from the energized MicroGrid

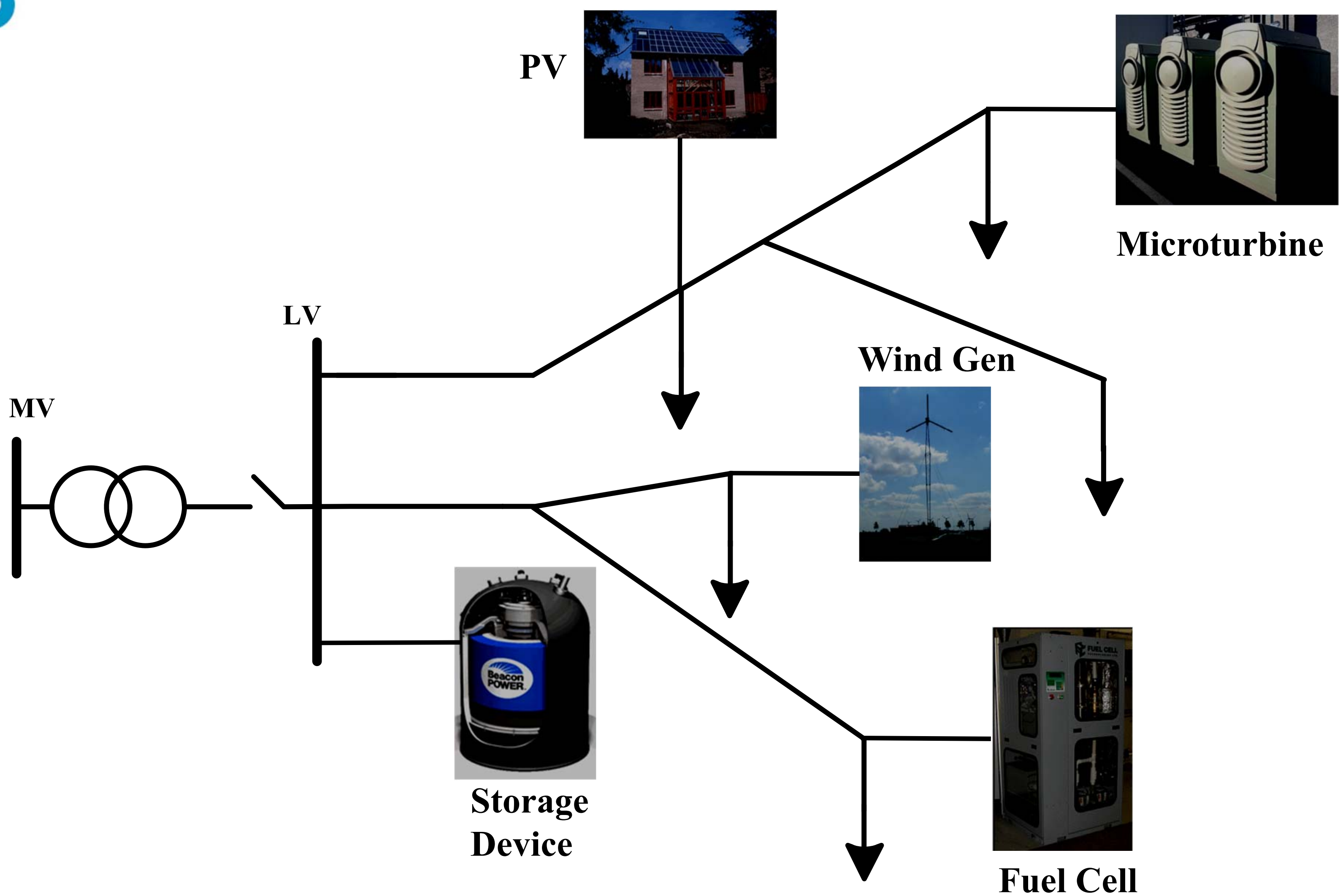
MG Black Start – Sequence of Actions

- Change the MG control scheme to Single Master Operation
  - Batteries assumed to be installed in microsource's DC link are not suitable to respond to frequent load variations – charge/discharge cycles reduce significantly the life-cycle.
  - Flywheel storage systems can operate equally well on frequent shallow discharges and on very deep discharges.
- Reconnect to the main grid

MicroGrid Black Start

Fault in the upstream MV network followed by unsuccessful MG islanding

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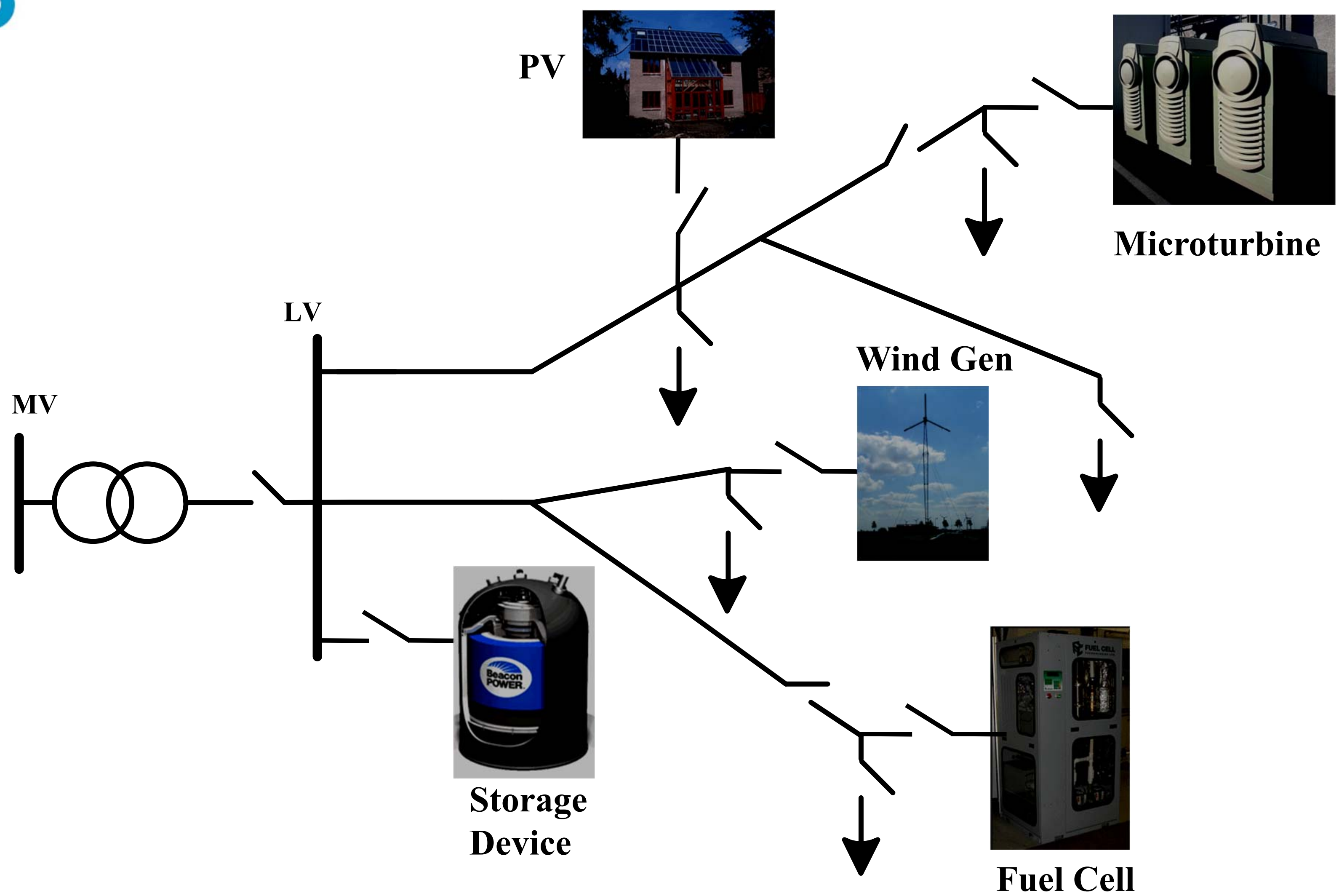
LV
Wind Gen
MV
Storage
Device
Fuel Cell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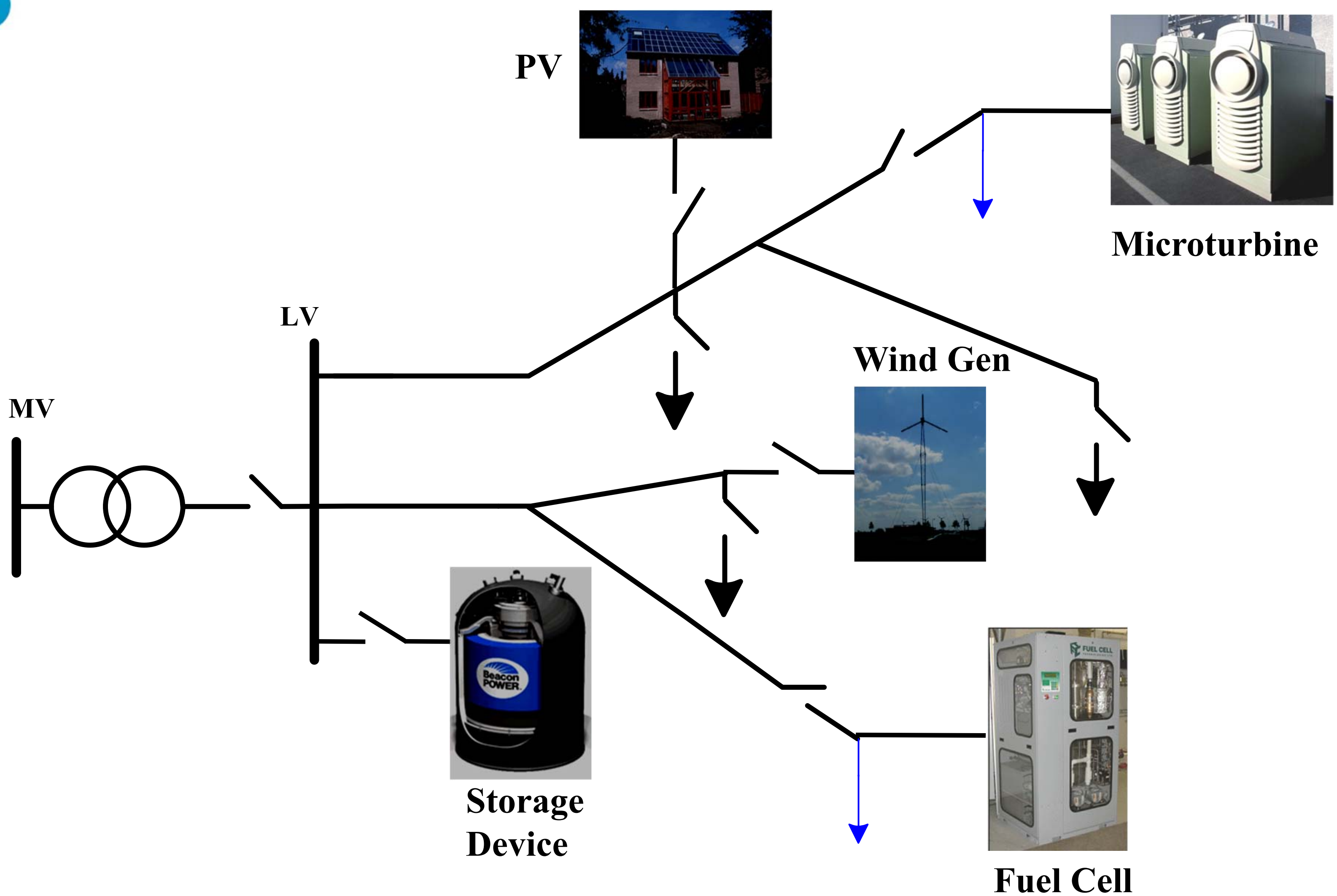
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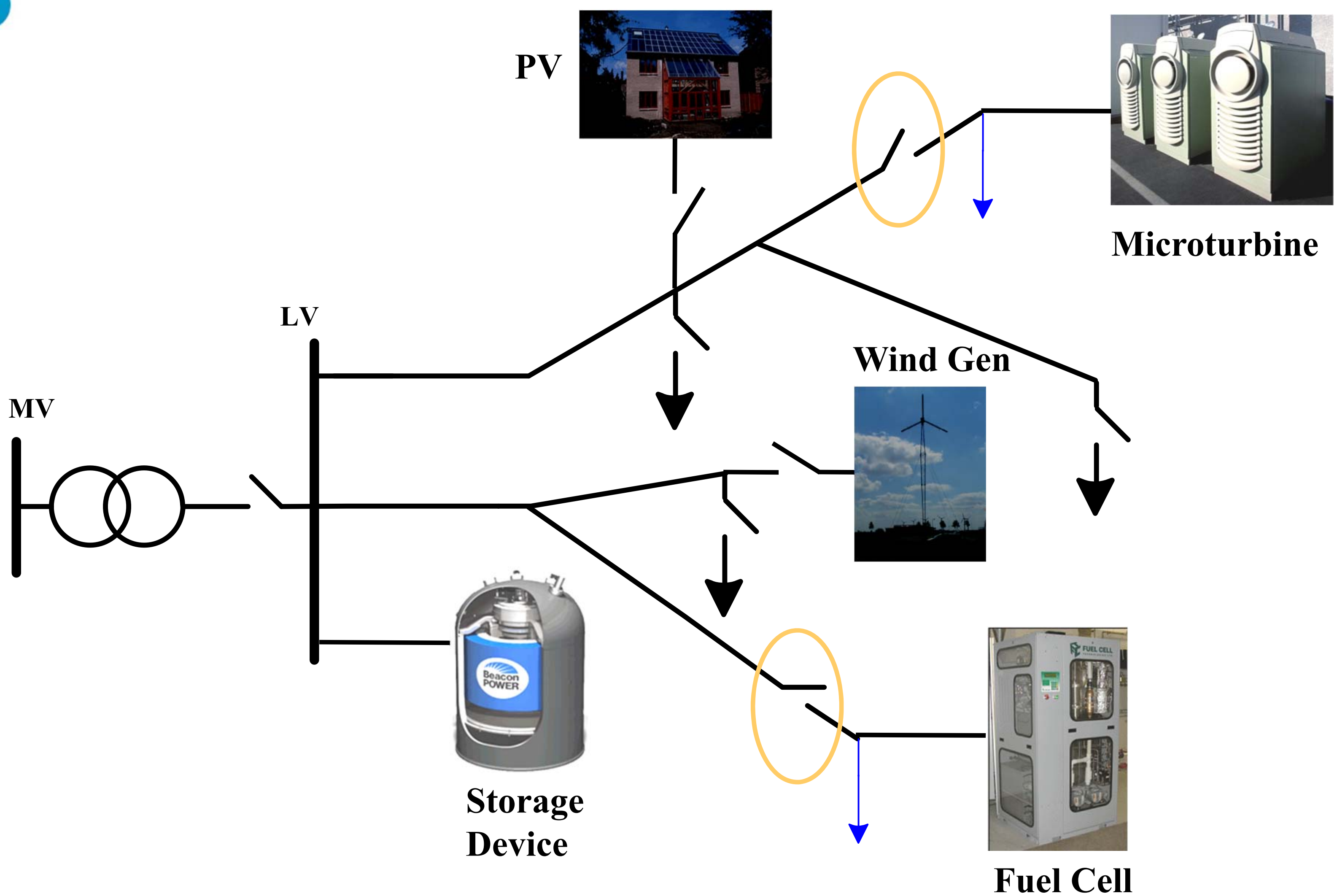
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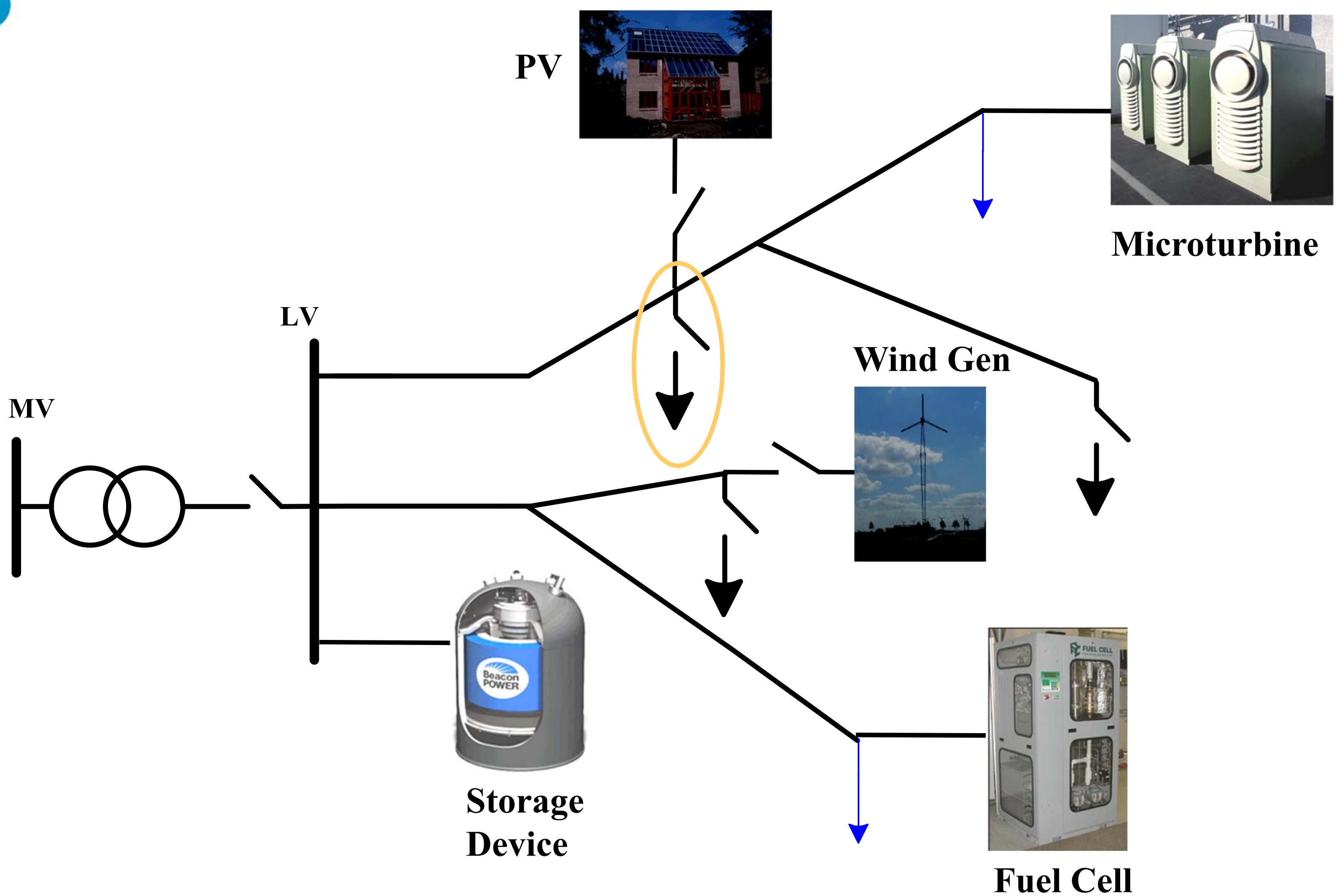
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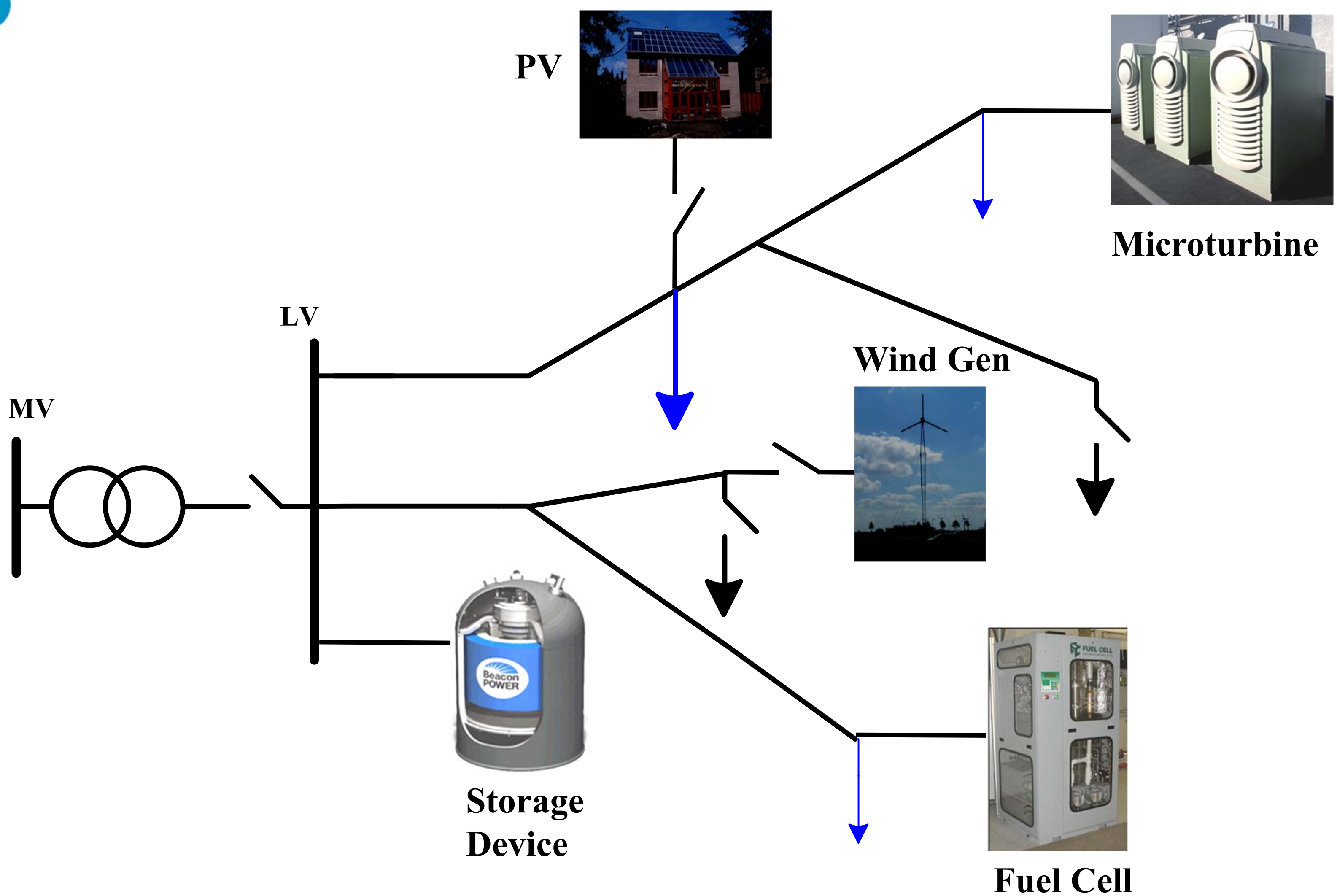
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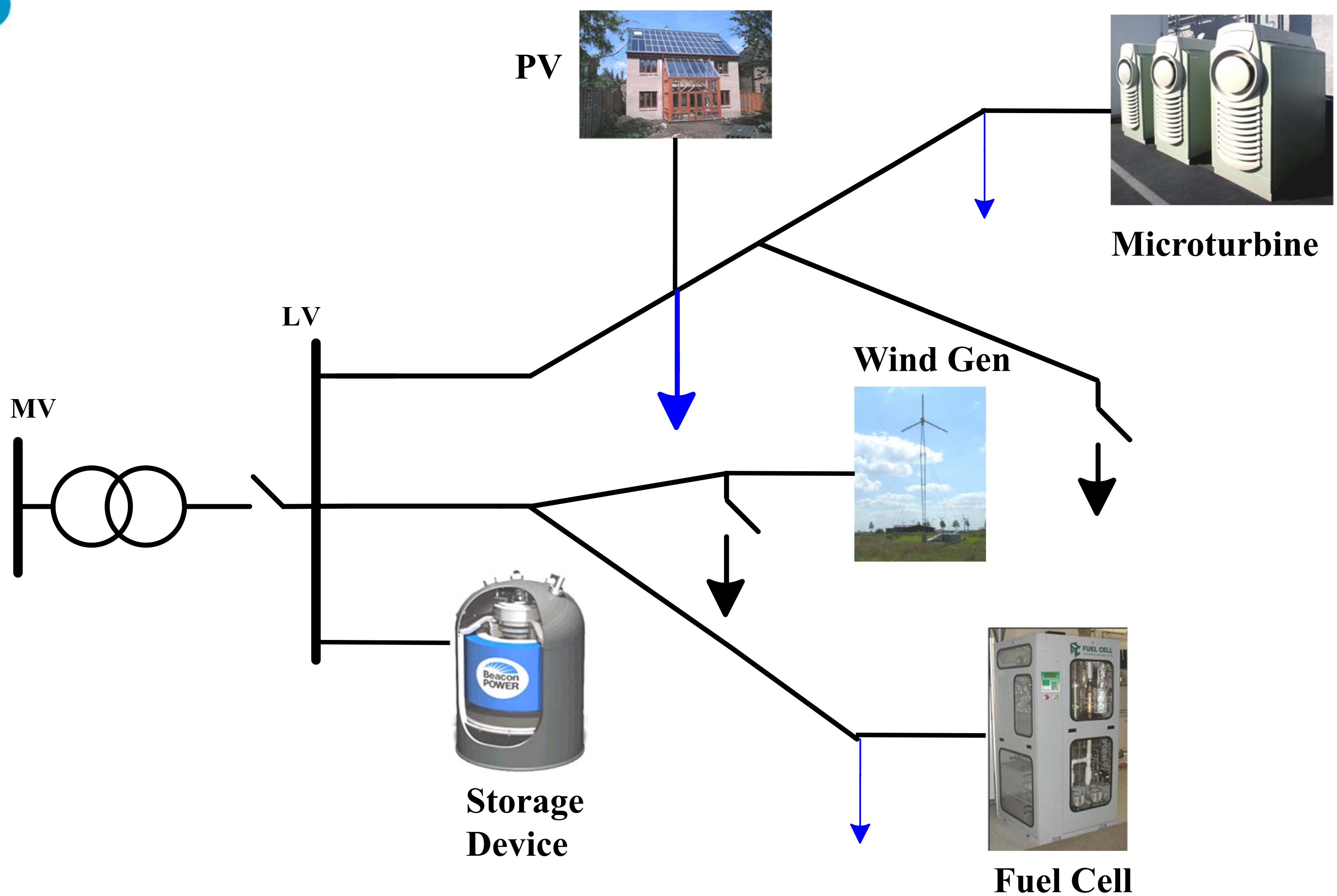
Fuel Cell
Beacon POWER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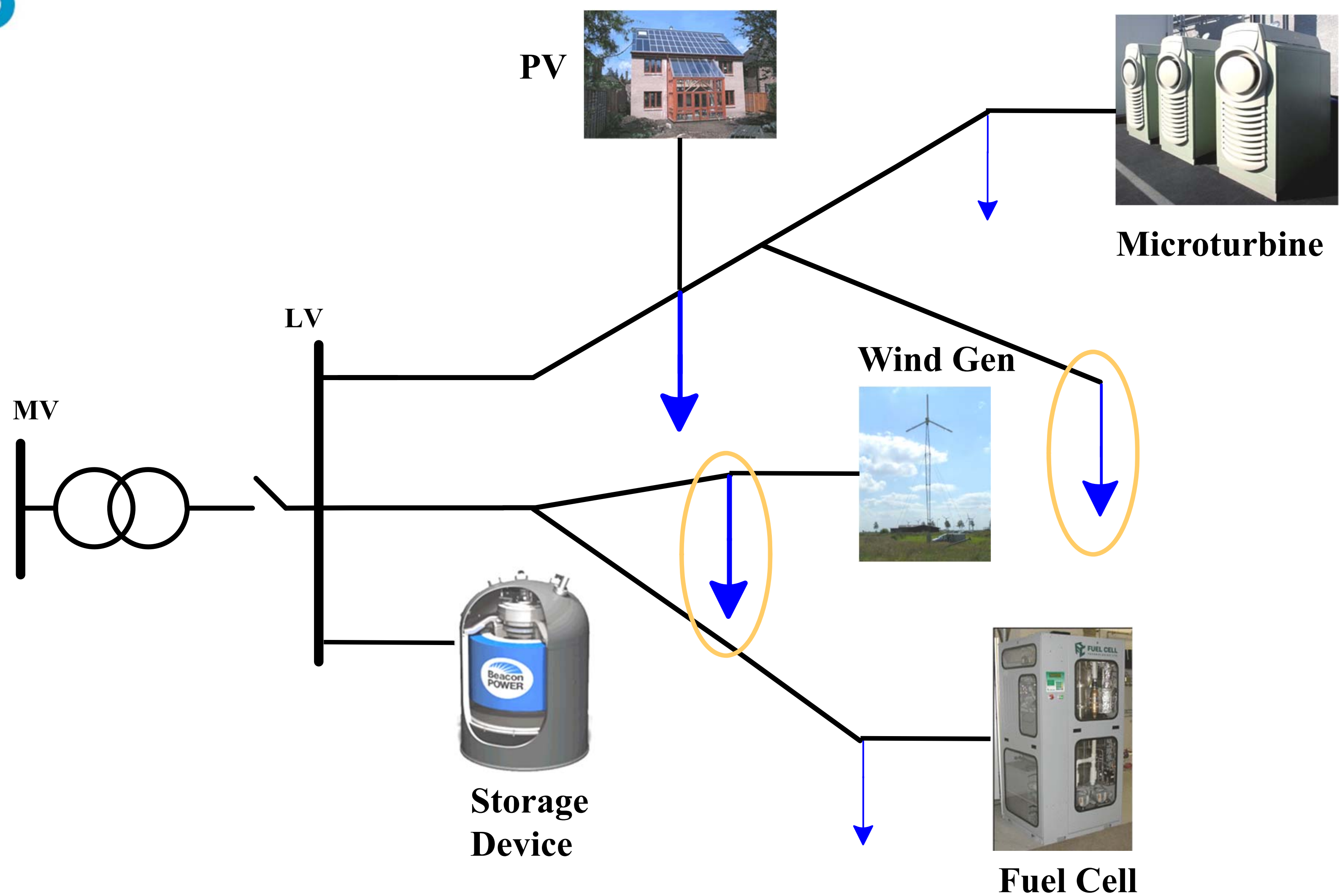
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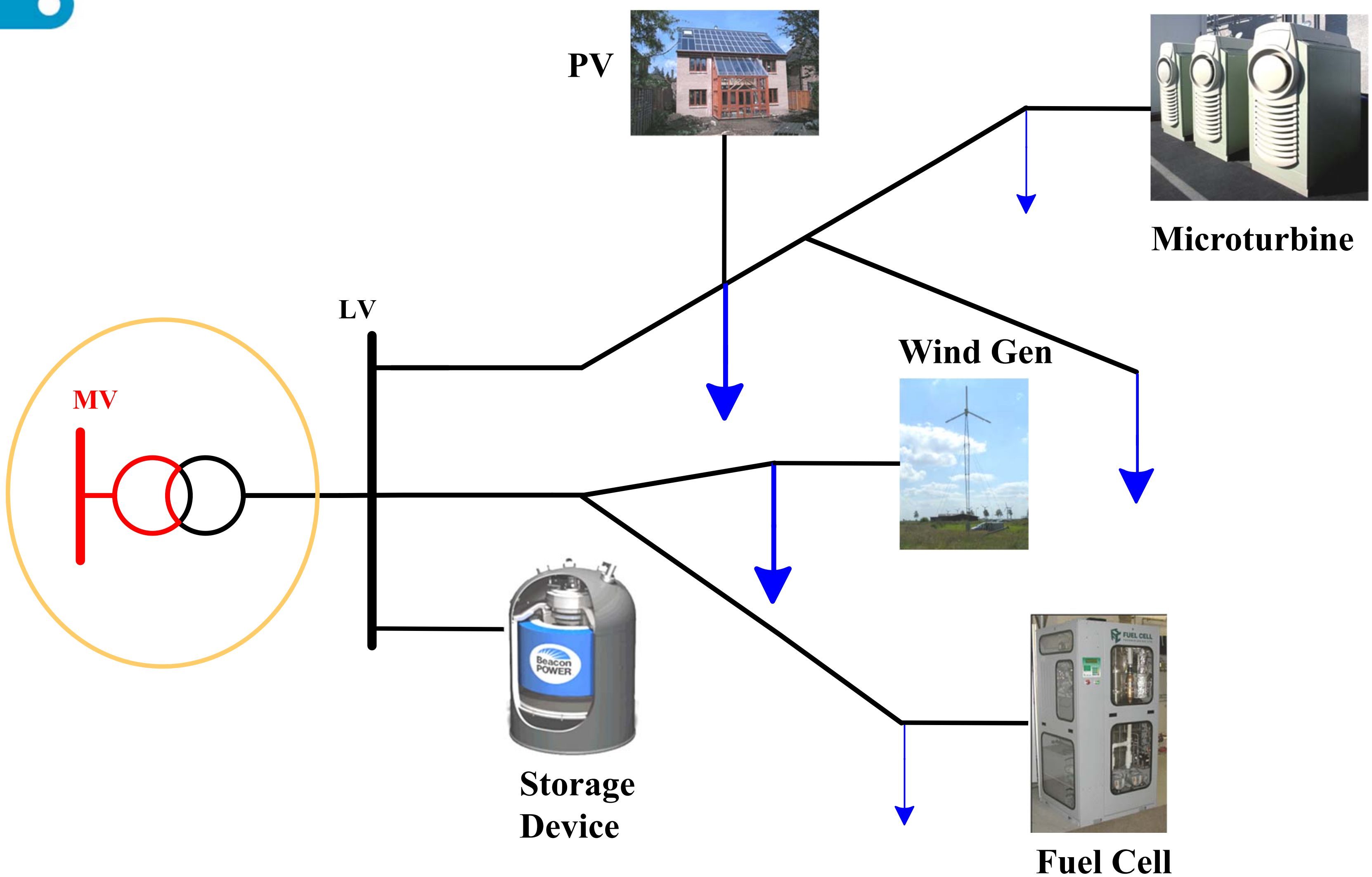
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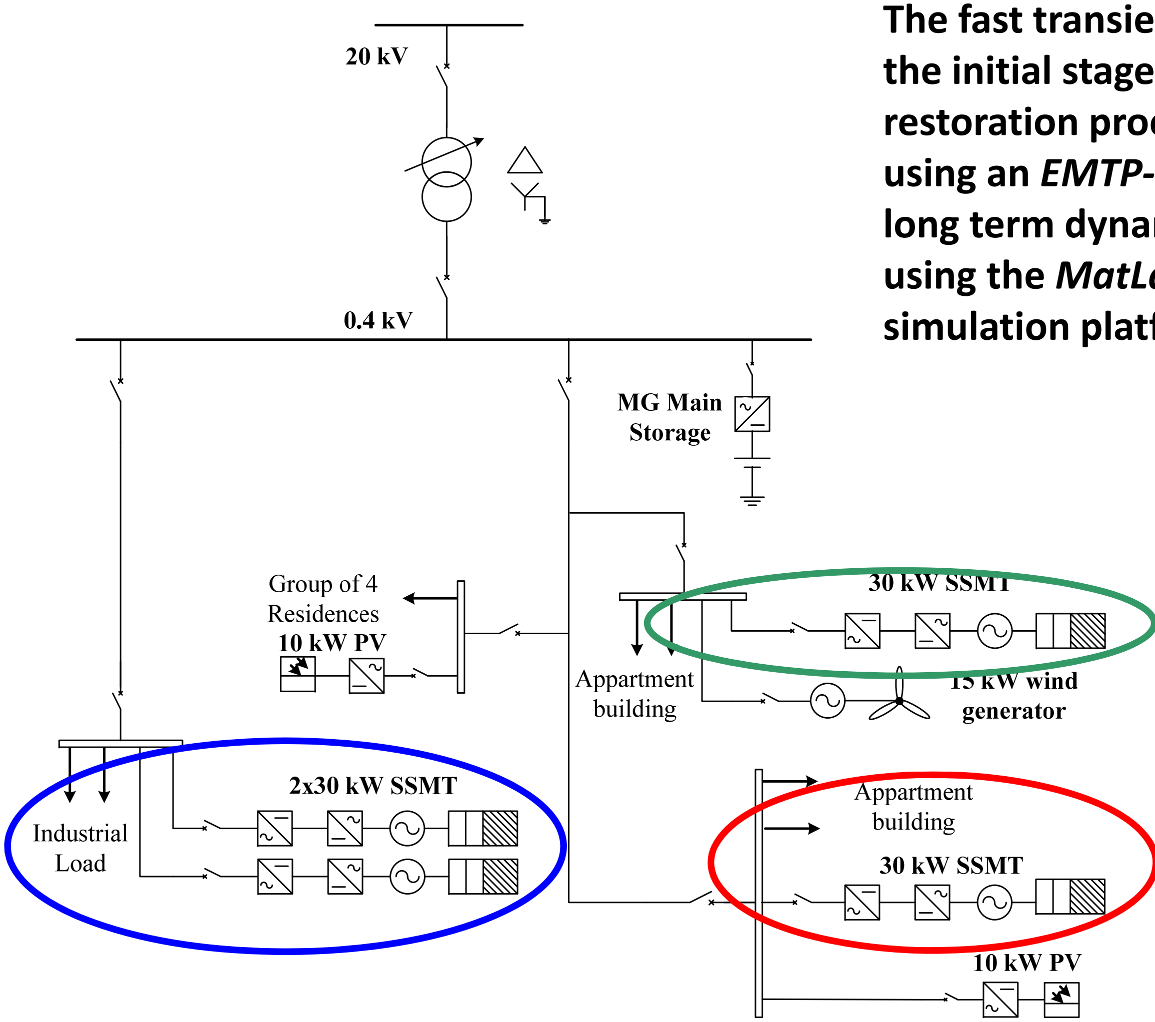
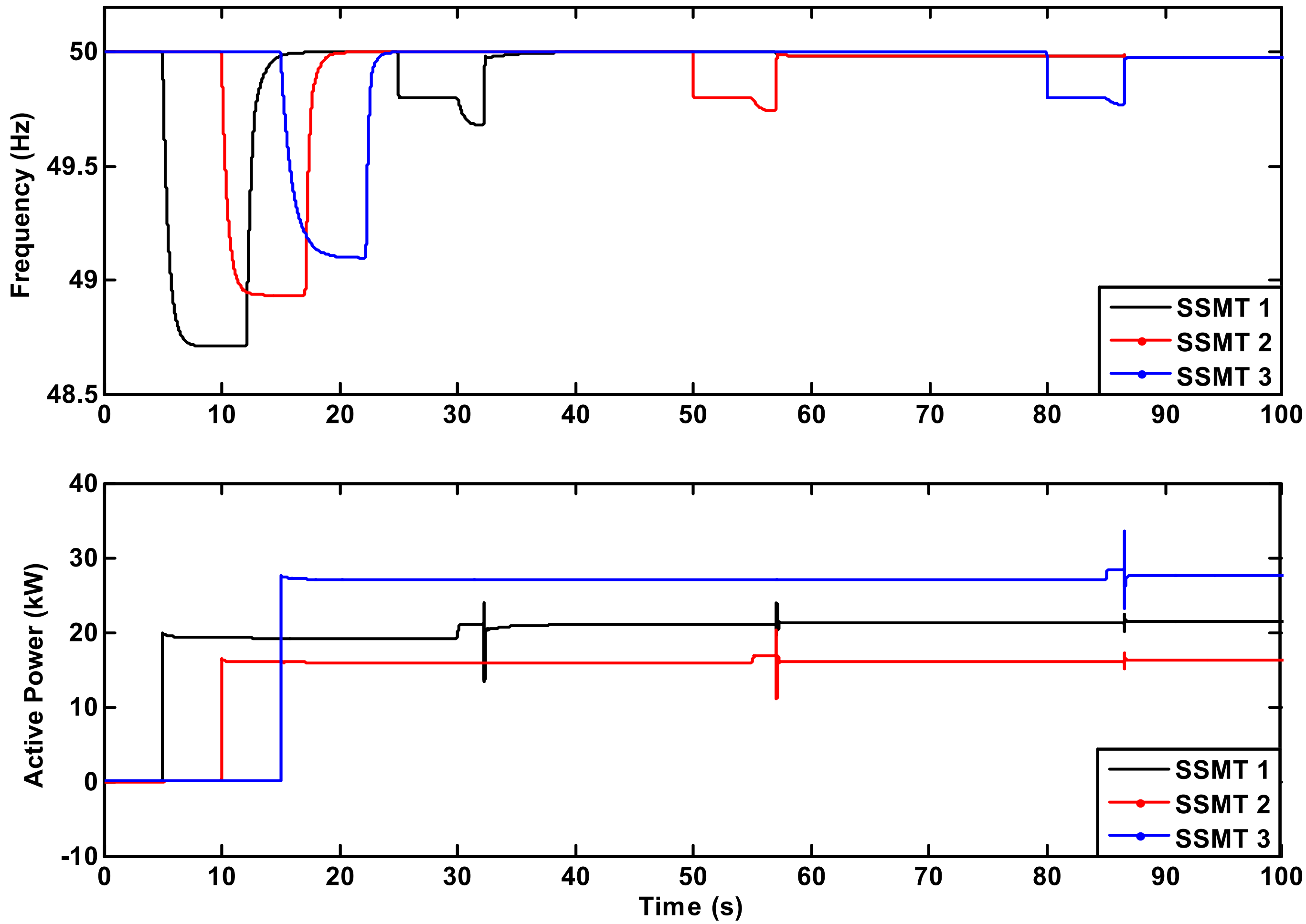
MG Black Start – Test System



The fast transients associated with the initial stages of the MG restoration process were analysed using an *EMTP-RV* tool, being the long term dynamics evaluated using the *MatLab Simulink* simulation platform

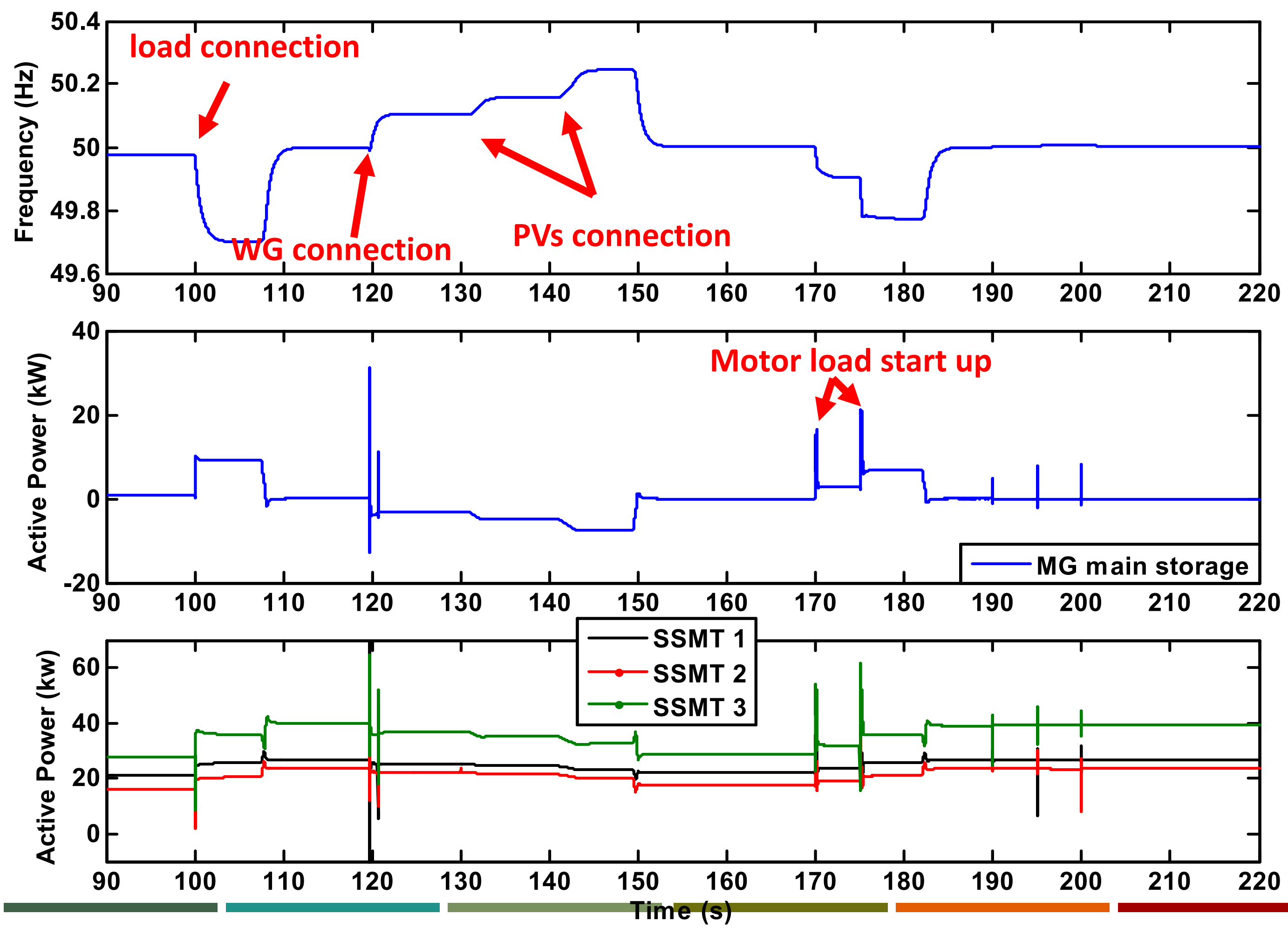
MG Black Start – Results

Small Islands Synchronization



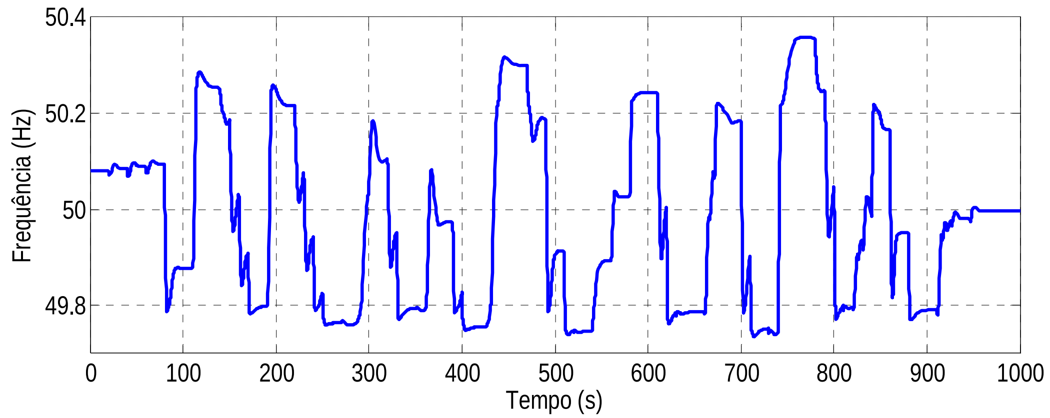
MG Black Start – Results

Development of the Service Restoration Procedure

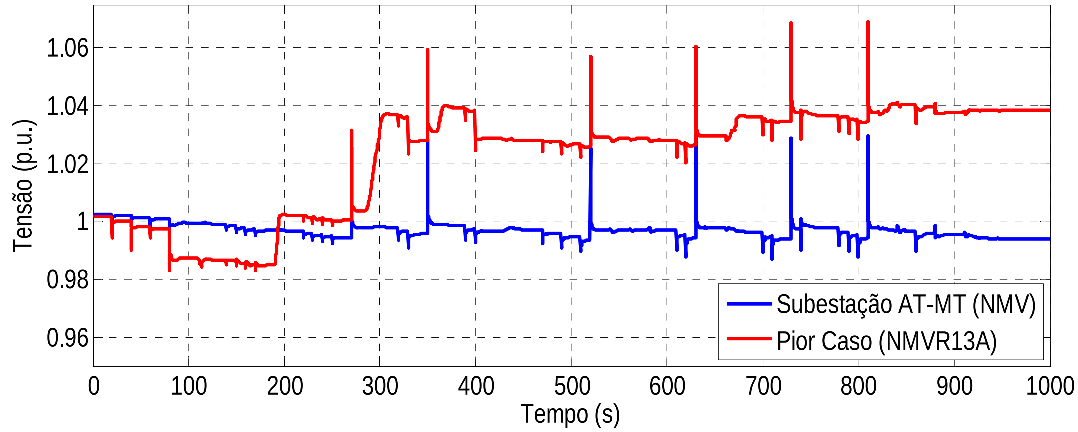


MV Restauration from the MV side

- Impact in frequency from a sequence of restauration actions



- Impact in the voltage from a sequence of restauration actions



Summary and Main Conclusions

- Key issues for a successful MG islanded operation:
  - An adequate sizing of storage devices coupled with static converters in order to provide efficient frequency and voltage control in the islanded MG
  - The implementation of efficient load-shedding mechanisms
  - Secondary load-frequency control
- Rules and conditions to be checked during the restoration stage by the MG components can be derived and evaluated via simulation to identify feasible procedures
- Hybrid bottom up / top down approaches can be adopted to reduce the total restauration time following a black, which will increase resilience of distribution grids and of the power system as whole.