Large Scale Integration of Micro-Generation to Low Voltage Grids

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Description of the laboratory micro grids

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1 Introduction

***This report provides technical descriptions of the laboratory micro grids*.**

Based on the hardware at the DeMoTec scaled micro grids (a single and a three phase grid) are set up including inverters, rotating generators and a MGCC. These inverter dominated grids are able to operate in the island and grid connected mode. Hence they will be an example for real a installation. Though they are scaled they have the full functionality.

A further test facility exists at UMIST, where a special flywheel of URENCO is commissioned and modified to provide stability for a MicroGrid. A possible application might be a dynamic voltage restorer.

The most relevant micro source models, which will be developed in WP_A is validating a the test beds of ARMINES. Therefore, suitable procedures are developed and measurements are carried out.

GERMANOS has developed the test laboratory of Sunlight in order to study an Autonomous Power Supply System (APSS). The point is to analyse the operation of the system, to calculate the amount of energy savings, to point out its weaknesses, to propose solutions and optimise system' s operation.

ICCS/NTUA presents the laboratory-scale microgrid system. Which is either interconnected to the LV network (grid-tied), or in stand-alone (island) mode, with a seamless transfer from the one mode to the other.

2 The laboratory Microgrid system of NTUA

This report presents the laboratory-scale microgrid system, which has been installed at the National Technical University of Athens, within Workpackage H of the project. The microgrid comprises two PV generators, battery energy storage, controllable loads and a controlled interconnection to the local LV grid. Both the battery unit and the PV generators are connected to the AC grid via fast-acting DC/AC power converters. The converters are suitably controlled to permit the operation of the system either interconnected to the LV network (grid-tied), or in stand-alone (island) mode, with a seamless transfer from the one mode to the other.

An important upgrade of the inverter control systems was performed by ISET, in order to provide the inverters (mainly the batteries unit) with load sharing capabilities, as well as to improve the transfer from the island mode to the grid-tied mode and vice versa.

This report provides :

- A technical description of the system.
- The concept of the system controllers.
- The operation of a MultiAgent System (MAS), which has been installed within the NTUA Microgrid.
- The implementation of a controllable load.

System description

The composition of the microgrid system is shown in ***Fig. 1***, along with a photo of the actual installation. It is a modular system, comprising a PV generator as the primary source of power, as well as a second small PV module, added recently. The addition of a small WT is also planned for the immediate future. In Table 1 a short description of the microgrid components is presented.

All microsources are interfaced to the 1-phase AC bus via DC/AC inverters. A battery bank is also included, interfaced to the AC system via a bi-directional PWM voltage source converter. The microgrid is connected to the local LV grid, as shown in ***Fig. 1***.

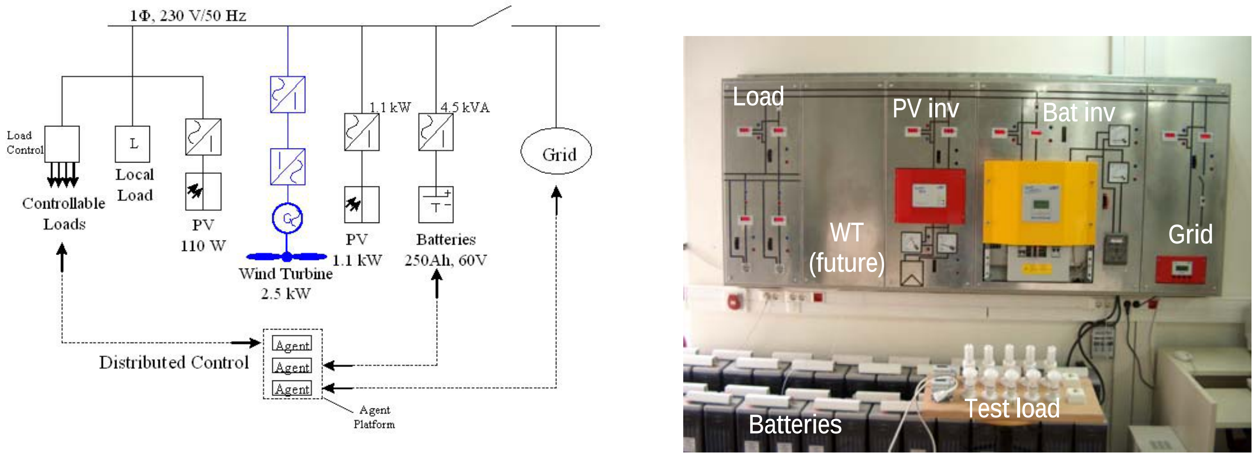


Fig. 1: The laboratory microgrid system (WT extension planned for next semester)

The central component of the microgrid system is the battery inverter, which regulates the voltage and frequency when the system operates in island mode, taking over the control of active and reactive power. The battery unit power electronics interface, schematically illustrated in ***Fig. 2***, consists of a Cuk DC/DC converter and a voltage source PWM inverter, both bi-directional, permitting thus charging and discharging of the batteries. The DC/DC converter provides the constant 380 V DC voltage to the DC/AC converter input. The HF transformer, operating at 16.6 kHz, provides electrical isolation between the battery bank and the grid. The four-quadrant DC/AC converter comprises a single phase IGBT bridge, output filters and a grid-connection inductor.

Main Components	***Description***
PV generator 1	→Modules : 10 series connected - Single crystal Si, 110W, 12 V per module →Inverter: SMA/Sunny Boy/1100 W
PV generator 2	→Modules : 1 - Single crystal Si, 110W, 24 V →Inverter: Soladin grid connected solar inverter 120 W
Batteries	→Cells: Lead-acid, vented type, 30 cells, 2 V, 250/370 Ah →Inverter: SMA/Sunny Island/4.5 kVA, bi-directional, suitable for grid-connected and islanded operation
Grid	→ Connection to local building distribution (lab switchboard) → MCB for protection – Contactor for control
Load	→ Passive (switchable resistive, inductive, capacitive) → Lighting (incandescent, CFL) → Small motor and other available appliances → Controllable load

Table 1 : Short description of the microgrid component

The battery inverter operates in voltage control mode (regulating the magnitude and phase/frequency of its output voltage), acting as a “grid-forming” unit, when the microgrid operates in island mode, i.e. setting the voltage and frequency of the system. When the microgrid operates in parallel to the grid, in which case the latter defines the operating frequency and voltage, the inverter operates as a “grid-following” unit.

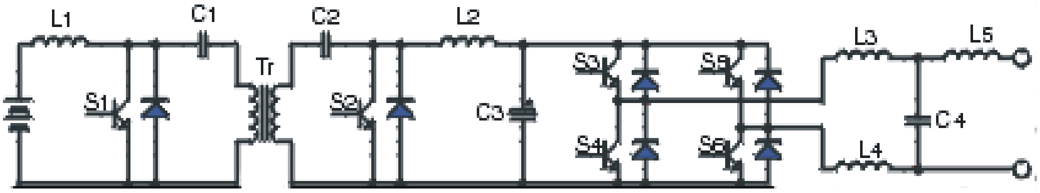


Fig. 2: Power section of the battery inverter, [3].

The PV inverters perform the MPPT function of the photovoltaic generators and operate as “grid-parallel” units, responsible for maximizing the PV power output, but without any participation in the voltage or frequency regulation.

Connection to the LV grid

The connection to the grid **before** the upgrade of the controllers, is shown in ***Fig. 3***. The basic idea of the configuration shown in ***Fig. 3*** was to switch the microgrid to island mode as soon asthe grid fails . For this purpose, the “Diesel synch. input” detected the absence of grid voltage and ordered the switch K3 to open. Upon the grid restoration, the Sunny Island detected the voltage presence and switch K3 closed, interconnecting the microgrid to the LV grid. In this way, a grid failure was automatically detected and the microgrid was transferred to island mode. However, the transfer form one mode to the other was not uninterruptible.

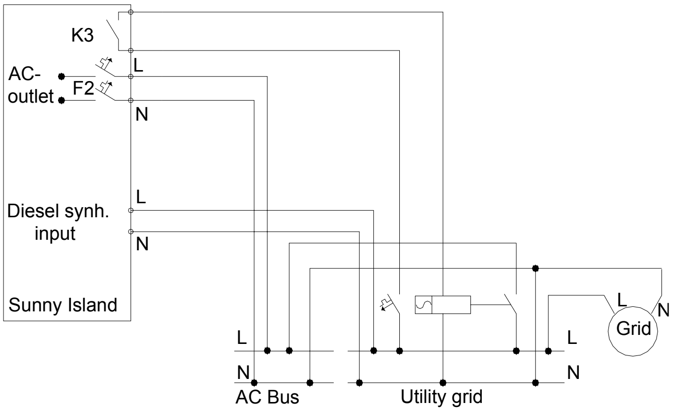


Fig. 3: Grid-connection scheme before the controllers upgrade

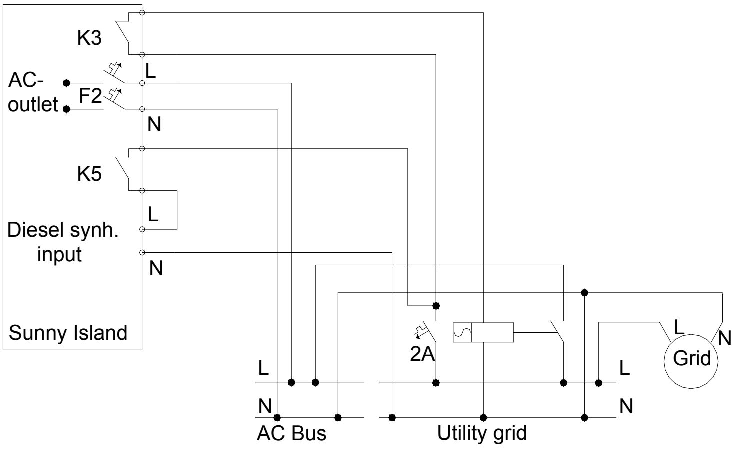


Fig. 4: Grid-connection scheme after the controllers upgrade

The grid-connection scheme after upgrading the controllers is shown in ***Fig. 4***. In the above configuration, the transfer from island to grid-tied mode and vice versa is controlled by the switch K5, which enables (or not) the “Diesel synch. input” to detect the grid voltage presence and thus give the appropriate order to the switch K3. In this new scheme, the transfer from one mode of operation to the other is now uninterruptible.

However, there is still no function implemented for the fast detection of public grid failures and subsequent isolation of the microgrid. That is, at present, the transfer from interconnected to isolated operation is seamless provided that the grid has not failed. A fast measurement and detection system is therefore required to enable the timely isolation of the system in case of abnormal grid conditions.

MultiAgent System for MicroGrid Operation

In this section, the capabilities offered by MultiAgent System (MAS) technology in the operation of the microgrid are presented. The use of MAS technology can solve a number of specific operational problems:

- The small DG (Distributed Generation) units have different owners, so centralized control is difficult. Several decisions should be taken locally.
- Lack of dedicated communication facilities.
- Microgrids will operate in a liberalized market, so the decisions of the controller of each unit concerning the market should have a certain degree of «intelligence».

The local DG units besides selling power to the network have also other tasks: producing heat for local installations, keeping the voltage locally at a certain level or providing a backup system for local critical loads in case of a failure of the main system. These tasks reveal the importance of the distributed control and autonomous operation.

The Agents in the Jade platform

Description of the Agents

In application that was developed for the Microgrids MAS there are 4 kinds of agents:

- Production Unit: This agent controls the Battery Inverter of the Microgrid. The main tasks of this agent are to control the overall status of the batteries and to adjust the power flow depending on the Market Condition (prices).
- Consumption Unit: This agent represents the controllable loads in the system. It knows the current demand and makes estimations of the energy demand for the next 15 minutes. Every 15 minutes it makes bids to the available Production Units in order to cover the estimated needs.
- Power System: This agent represents the Main Grid to which the Microgrid is connected. According to the Market Model presented before, the Power System Agent announces to all participants the Selling and the Buying price. It does not participate in the market operation since it is obliged to buy or sell any amount of energy asked for (as long as there areno security issues for the network)
- MGCC: This agent has only coordinating tasks and more specifically to announce the begining and the end of a negotiation for a specific period and to record final power exchanges between the agents in every period.

Behavior/Actions

In this section the behavior of the agents will be described. The behavior of every agent has two main parts:

- Initialization in which every agent announces its services to the DF agent.
- Normal Operation which includes all the tasks and actions that every agent performs. In the following paragraph the behavior of every agent will be presented separately. All the agents use cyclic behavior.

MGCC: This agent performs two main tasks. The first is to record every message of type *"Record"* and the second is to announce the period of the negotiation. According to the market description, no energy exchange within the Microgrid is active unless recorded in the MGCC in order to avoid double assignments.

Power System: This agent announces the Grid sell/buy price to all agents that participate (according to their service declarations) in the Market. The announcement is made just after the end of the negotiation period or whenever there is a change in the prices. In order to simplify the start up of the other agents, it is not allowed for a market agent to bid in the market if it has not received at least one announcement for the grid prices. This means that the new agent that was launched will bid in the next period.

Consumption Unit: This agent has currently two tasks. The first task is to make an estimation for its energy needs for the next period and the second is to participate in the market.

- Energy estimation: In the present application, this estimation is based on the current power demand, assuming that this demand will remain constant for the next 15-20 minutes.
- The market operation: The agent sends an offer to all available sellers for a price higher than the price BP that the Grid would buy. If the agent does not receive any “accept” message then it increases the bid and the cycle continues, as long as the bid is lower than the sell price SP of the grid. After that it is obvious that it is to the interest of the agent to buy energy directly from the Grid.

Production Unit: This agent only receives offers from the consumption units and makes decisions according to its operating cost and available power.

Communication between Agents and Local Sources/Loads

One of the main difficulties for the development of the system is to establish the communication between the agents and the hardware (inverters). The main method for communication is through OPC [OLE for Process Control, where OLE stands for Object Linking and Embedding] servers/clients as shown in ***Fig. 5***. This method was selected since the manufacturer of the inverters (SMA) has made available a suitable OPC server.

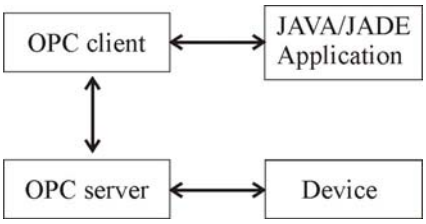
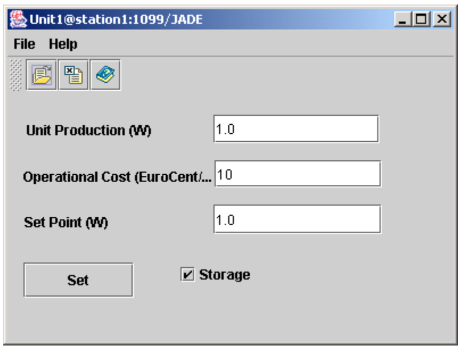


Fig. 5: Communication method between the microgrid components (electrical devices) and the MAS application

Software Operation

In ***Fig. 6*** a screenshot of the GUI of the agents is presented, which permits changes of the operational cost . Similar forms have been developed for the Loads and the Main Grid.



Unit Production (W) 1.0

Operational Cost (EuroCent/... 10

Set Point (W) 1.0

☑ Storage

Fig. 6: Screenshot of the GUI for the Production Unit

In the implementation that developed in NTUA, the main target is to produce or store a certain amount of energy in a specific time period and this is done with a procedure that calculates the droop frequency set point. This calculation is very fast,but due to communication limitations this set point can be sent to the inverter only every 4-5 seconds. This large period of time does not permitthe power production to remain absolutely constant, since the grid frequency changes more rapidly. On the other hand, the 4-5 seconds delay is not a problem when dealing with energy generation over intervals of 10 or 15 minutes. This routine is implemented inside the agent that is controlling the production units.

Controllable load

For the effective cooperation of the MAS technology with the microgrid a controllable load is required, which will be linked to the Consumption Unit agent. The Consumption Unit agent will have measurements in order to estimate the consumption and to make more realistic bids. Furthermore this agent will have the ability to control the load and to limit it according to the market status or the microgrid security considerations. So a controllable load scheme has been implemented, as described below.

This section describes the controllable microgrid load, which is implemented using various load types and a relay panel (***Fig. 7***), controlled either manually or by a PLC (Programmable Logic Controller) or a PC-Card. Currently, the PLC shown in Figure 11 is used to control the relay panel.

The relay panel is connected to a 25-pin parallel port, to facilitate the connection of the control panel to the PLC or a PC Card. Controlling each relay via the parallel port, the respective load is controlled independently. The panel is sufficient for controlling up to eight different loads of rated current up to 16A.

In order to permit the direct control of the panel from a PC Card or a PLC, secondary 5 to 24 V DC relays are first used to drive the 230 V AC relays, which subsequently control the loads, as shown in ***Fig. 8***.

Fig. 7: PLC used to control the relay panel of the switchable loads.

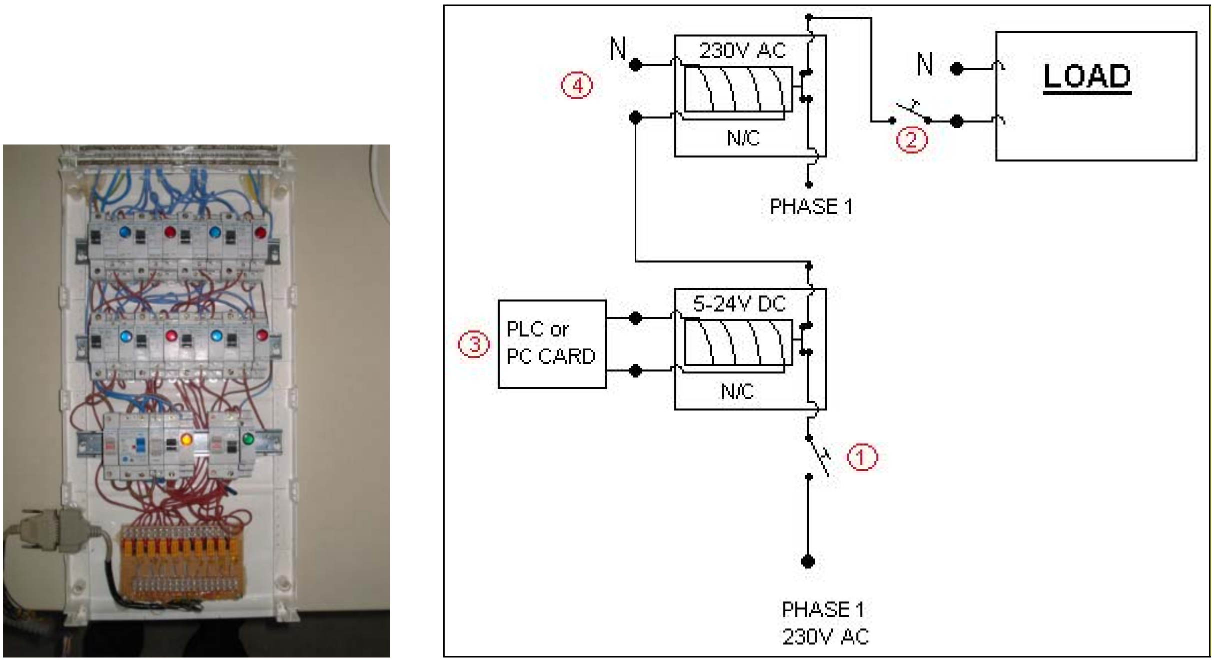


Fig. 8: Relay panel and control implementation

A variety of load types can be incorporated in the microgrid model. Such are variable resistors, capacitors, inductors, lighting loads (incandescent and CFL lamps), single-phase induction motor loads, shown in ***Fig. 9***, as well as a variety of AC appliances available in the lab.

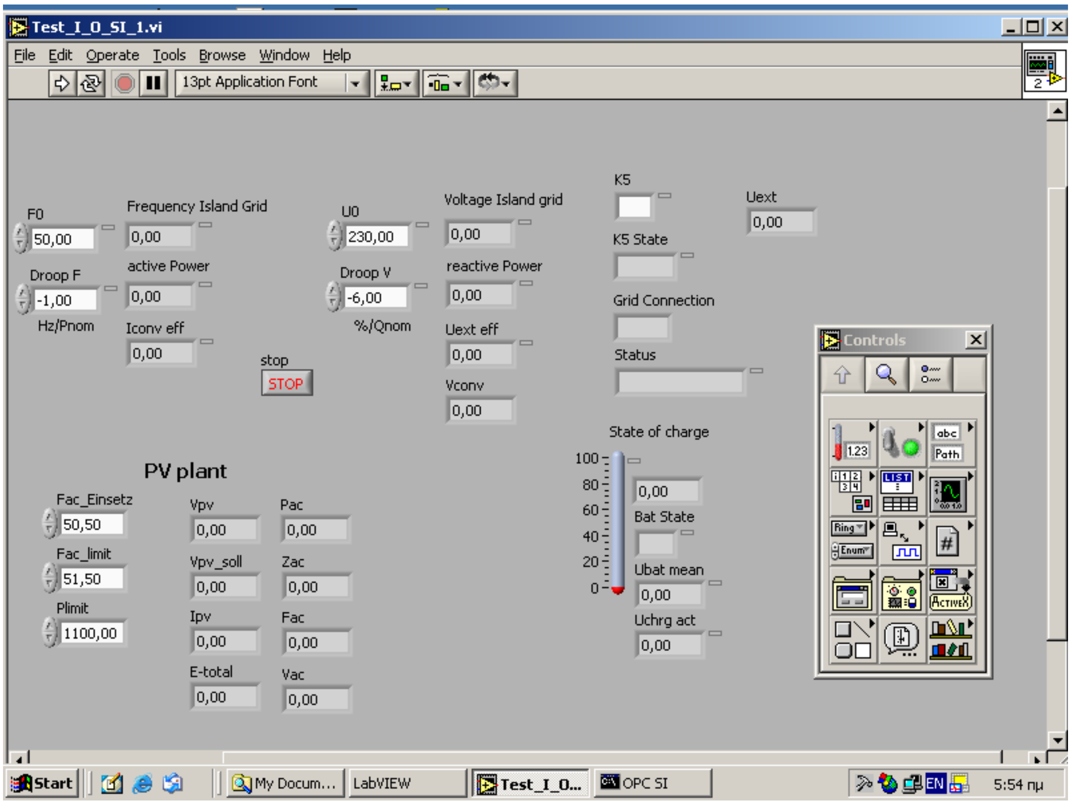
Fig. 9: Available loads for the microgrid

Monitoring and control system

Using the form of communication described in Section 4.2, two monitoring and control systems were implemented, developed inWinCC and LabView environment and shown in **Fig. 10** and **Fig. 11**. These systems provide, first of all, measurements from the battery and the PV –inverters (voltage, current and frequency of the inverters, state of the batteries etc.). In addition, they can alterthe “idle” frequency (f_0) and voltage (u_0), as well as the corresponding “droop” values (Section 2.3). In this the active and reactive power output of the battery inverter can be regulated. Furthermore, the grid synchronization can be also controled (via the relay K5 of the Sunny Island inverter).

Trend	Tag Connection	Value	Date/Time
Power Production	WinCC_Pconv	-440.000000 i.	1/5/2004 5:35:37.968 PM
Frequency	WinCC_Fconv	49.929999 i.	1/5/2004 5:35:37.968 PM
Frequency SetPoint	WinCC_403_Fconv_nom	50.000004 i.	1/5/2004 5:35:37.968 PM

Fig. 10: Monitoring and control system in WinCC



F0 50,00
Frequency Island Grid 0,00
U0 230,00
Voltage Island grid 0,00
K5
K5 State
Uext 0,00
Droop F -1,00 Hz/Pnom
active Power 0,00
Droop V -6,00 %/Qnom
reactive Power 0,00
Grid Connection
Iconv eff 0,00
Uext eff 0,00
Status
stop STOP
Vconv 0,00
State of charge 0,00
Bat State
Ubat mean 0,00
Uchrg act 0,00

PV plant
Fac_Einsetz 50,50
Fac_limit 51,50
Plimit 1100,00
Vpv 0,00
Vpv_soll 0,00
Ipv 0,00
E-total 0,00
Pac 0,00
Zac 0,00
Fac 0,00
Vac 0,00

Fig. 11*:* Monitoring and control system implemented in LabView

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3 Design Centre for Modular Systems Technology (ISET)

The Concept of “DeMoTec”

The Design Centre for Modular Systems Technology “DeMoTec” is used for development, demonstration and information transfer of the latest trends in electricity supply using renewable energy (RE) technology. Concerning technology demonstration, DeMoTec integrates full scale prototype systems which represent the different areas of the electricity supply technology (e.g. decentralised generation, rural electrification, solar home systems, etc.). With these components experiments, training and demonstration can be carried out under real operating conditions. Visual and hardcopy information facilitate the DeMoTec visitors and users from different sectors (general public, technicians, engineers, postgraduates) to understand the operation principles of components or systems of interest. The DeMoTec includes an area of nearly 600m^2 (See ***Fig. 12***).

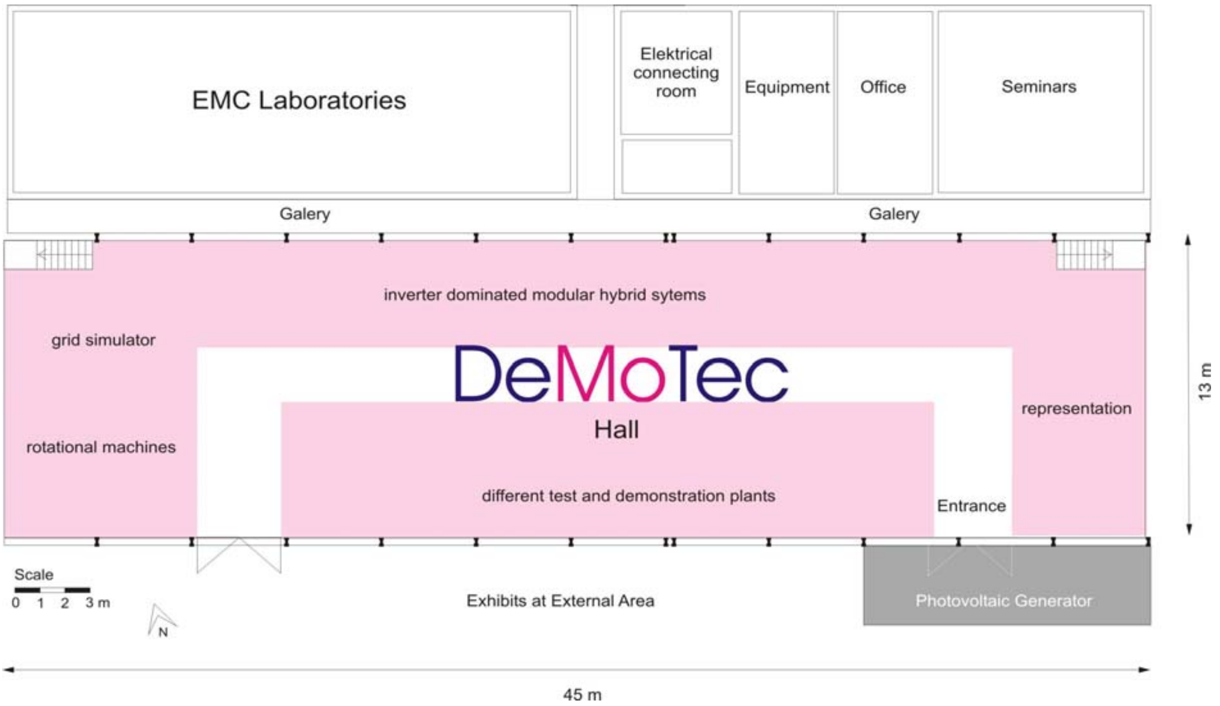


Fig. 12: Areas of DeMoTec

Plants and devices of the DeMoTec

DeMoTec comprises different RE components and systems. ***Fig. 32*** gives an overview of the plants and technical infrastructure of DeMoTec. They will be described more exactly in the following paragraphs.

Generator sets

Diesel generator set: The diesel generator unit consists of a diesel motor (31.4 kW) and a three-phase synchronous generator (400 V, 50 Hz, 32kVA, cosφ=0.8, see ***Fig. 13***). The plant is a commercial unit produced by *Polyma*.

Fig. 13: Diesel aggregate

Speed variable diesel aggregate: In close cooperation, the companies *SMA Regelsysteme GmbH* and *Kirsch GmbH* have developed a modern speed variable diesel aggregate consisting of a diesel motor (30kW), a synchronous generator (400 V, 50 Hz, PME 20kVA) and a three-phase inverter (***Fig. 14***). The speed variable operation (1200 to 3000 min^{-1}) of electricity supply units has several advantages during partial load:

- lower fuel consumption
- lower sound emission
- less wear out resulting in an increased life time

Fig. 14: Speed variable diesel aggregate

Combined heat and power (CHP) station: In order to analyse the influence of an emulsion consisting of diesel oil, plant oil and pyrolysis oil on the performance of standard diesel engines, a special CHP unit has been set up in DeMoTec. The test facility allows the adjustment of different electric and thermal loads for grid connected and stand-alone operation, in order to analyse different fuel mixtures. Besides the efficiency of the motor, the influence on the exhaust gases are under investigation. The motor induction generator set has a nominal electrical rating of 5,5 kW (***Fig. 15***).

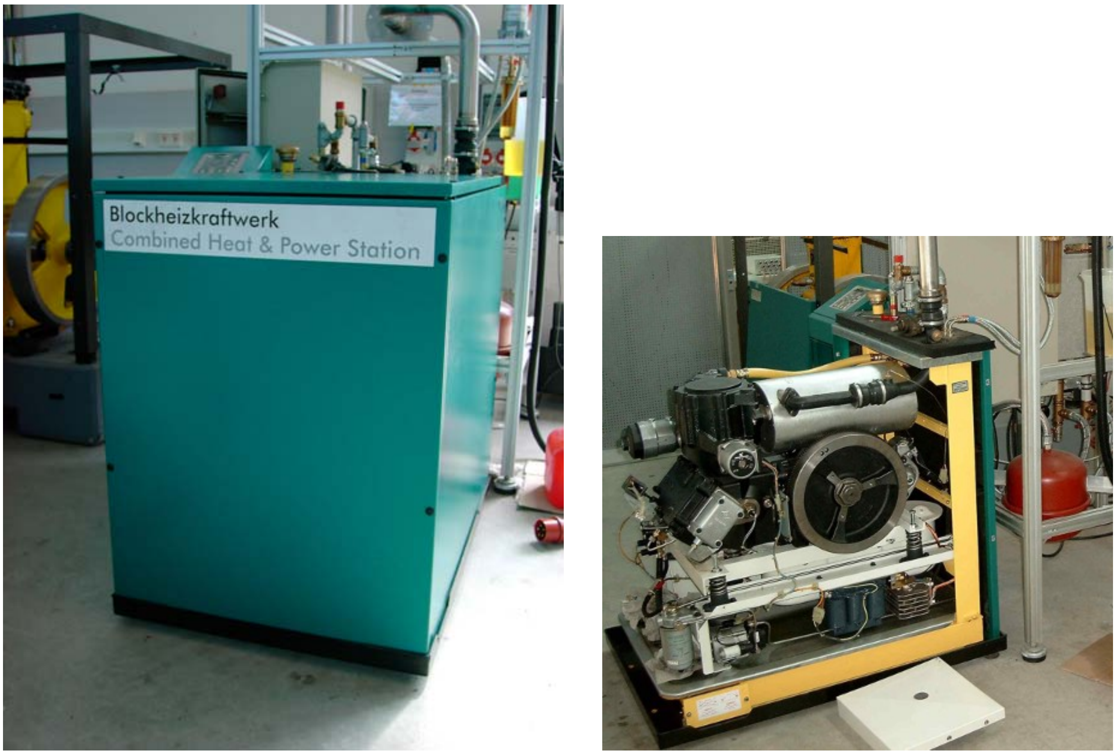


Fig. 15: CHP station

Electric machines

Grid simulator: In order to simulate an electric grid a motor-generator set has been built up. The plant consists of a converter supplied DC-motor and a synchronous machine (three phase) with a total power of 80 kVA (***Fig. 16***). It is suitable for a nominal frequency of 50 and 60 Hz.

Fig. 16: Grid simulator

Mini-grid simulator: In order to simulate small wind and diesel-gensets, a special motor generator set has been set up. The set consists of a drive controlled motor and a synchronous generator respectively induction generator. The type of generator can be selected by mounting the desired generator on the test bed. The total power of the motor generator set is *15 kVA* (***Fig. 17***).

Fig. 17: SG-IG plant

Wind energy converter (WEC) simulator: The Wind energy converter (WEC) simulator consists of a converter supplied DC-motor, a flywheel and a three phase asynchronous generator (IG). It has a total power of 5 kW and is controlled by *Siemens S5* PLC (***Fig. 18***).

Fig. 18: 5 kW DCM-IG unit

Converters, batteries and loads

Battery bi-directional inverter: In order to investigate and improve the battery modes of operation (stand alone, charging mode and grid parallel mode) in hybrid systems, a bi-directional inverter has been developed by IEE, ISET and SMA. The modular hybrid system structure (see ***Fig. 24***) has been used for testing and development of these bi-directional battery inverter "Sunny-Island" (S_n=*4,5 kVA*, ***Fig. 19***).

Fig. 19: Sunny-Island Inverter

"Virtual Battery": based on a physical model for lead-acid batteries, a virtual battery has been developed. By means of a real-time version of the battery model *ISET-LAB* the output of a DC power supply unit is controlled according to the terminal behaviour of a real lead-acid battery.

Meanwhile, several prototypes of the "Virtual Battery" have been constructed. These prototypes cover a voltage range up to 95 V, providing power of nearly 30 kW (***Fig. 20***).

Fig. 20: Virtual battery

Various types of single phase inverters: In order to perform examinations and investigations with grid connected PV inverters a special test field has been built up in the DeMoTec hall (***Fig. 21***).

Fig. 21: PV inverters

Loads: The power conditioning in modular systems technologies make it possible to supply different loads (***Fig. 22***). A workshop with typical loads like refrigerators, lamps, pump drive, drilling and welding machine have been build up in DeMoTec. Furthermore, it is possible to simulate loads by means of combination of R,L,C elements (***Fig. 23***).

Power Data of the Loads:

Water disinfection	P_n=60 W
Refrigerator	P_n=70 W
Lamps	P_n=270 W
Mixer	P_n=400 W
Pump drive	S_n=600 VA
Welding equipment	S_n=2,5 kVA

Fig. 22: Workshop with different loads

Fig. 23: R,L,C load elements

Experimentation facilities

Modular Hybrid System: In order to promote the design, development and demonstration of modular system technology, IEE and ISET in cooperation with industrial partners have developed and constructed a modular hybrid energy system as can be seen in ***Fig. 24***. This system has realistic components sizes and serves as demonstration and development unit for the latest products of the company SMA. Also, it is used as a test plant for components performance evaluation and further development of the modular supply technology concept. The system contains three PV inverters (*Sunny-Boy; DC to AC, 700 W each)*, three battery bi-directional inverters (*Sunny-Island; each 3.3kW)* with battery bank (*14 kWh)* as backup and a Diesel-SG unit (12.5 kVA).

Fig. 24: Modular hybrid system (PV-battery-diesel system)

Photovoltaic-Battery Island System: AC Photovoltaic-Battery Island Systems are designed for providing standard 230V / 50 Hz AC power, in order to supply typical loads. The island system, connected via AC bus, contains two single phase PV inverters (*Sunny-Boy; DC to AC, 700 W each)*, three bi-directional battery inverters (*Sunny-Island; DC to AC & AC to DC)* with a battery bank (*14 kWh)*. The self-commutated battery inverters allow to sustain a local grid. Therefore, the operation of island and grid parallel modes can be investigated (***Fig. 25***).

Fig. 25: Photovoltaic-Battery Island System

Single phase mini-grid for supply of common AC loads: The objective is to design an expandable, low cost but standard quality mini-grid kit with multiple renewable and non-renewable energy power generators connected on the AC side.

A new mini-grid was constructed at DeMoTec in order to test in a single phase island grid the parallel connection of inverter coupled photovoltaic generators, batteries. The mini-grid containes two PV inverters (Sunny-Boy 850), a self-commutated bi-directional battery inverter (Sunny-Island) with battery bank and some typical loads (e.g. refrigerator and ventilator). The battery inverter is used as the master control for keeping grid voltage and frequency within acceptable limits (***Fig. 26***).

Fig. 26: Single phase mini-grid for supply of common AC loads

SINVERT solar hybrid system: The manufacturer *Siemens* has developed a hybrid unbreakable power supply (UPS) plant, which is controlled by *Siemens S7* PLC. The plant has been built up in DeMoTec and contains a 20 kVA PV inverter and a 30 kVA UPS unit. The PV inverter is supplied by the public net. A rectifier and a power controller simulate the typical PV characteristic. The UPS unit consists of a battery bank (80 Ah, 552 V) and a 20 kW Chopper. It can be supplied by the PV inverter, the public grid or optional by a Diesel gen set (***Fig. 27***).

Fig. 27: Hybrid UPS unit

Three phase inverter: In order to investigate high-power AC battery units the manufacturer *SMA* is developed a three phase self-commutated bi-directional battery inverter with a nominal rating of 70 kVA. See ***Fig. 28*** and his placement in DeMoTec Hall on ***Fig. 32***(No.11).

Fig. 28: Three phase inverter

Distribution System Simulator: The distribution simulator *(U_n=10 kV)* is a physical model, which consists of three interlinked transmission lines (overhead lines or cables, see ***Fig. 29***) and three transformers 100kVA/10kV/0,4kV. It is possible to investigate transmission behaviour of the network on the medium voltage level by varying length of the lines and cables, varying loads and different kinds of operating conditions, as well as resulting influence on the devices, which are connected on the low voltage side.

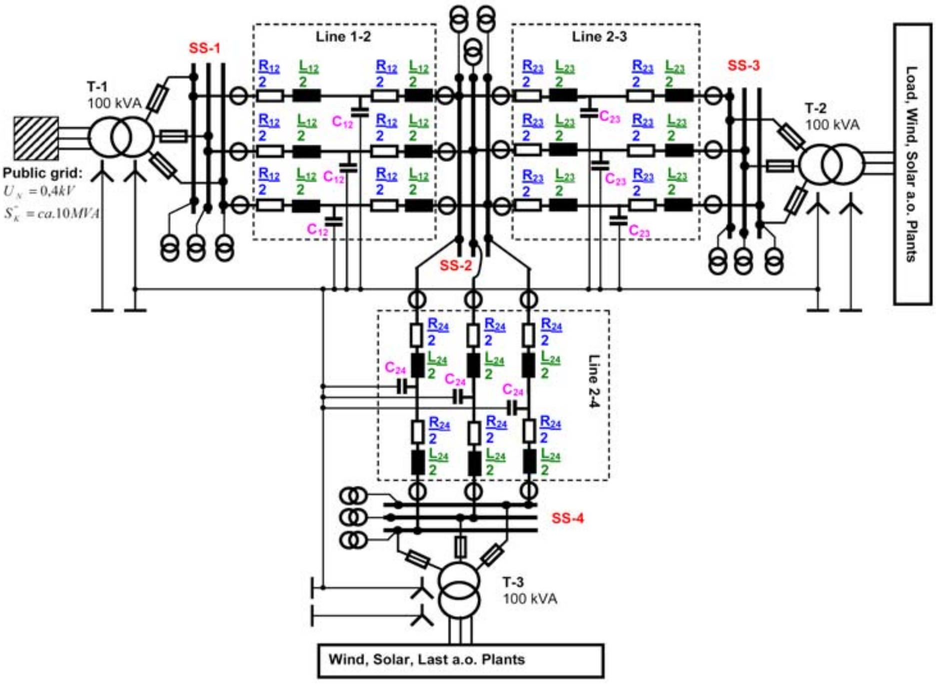


Fig. 29: Principle schema of 10 kV Hardware Network Simulator (Distribution System Simulator)

Fig. 30: General view of Hardware Network Simulator

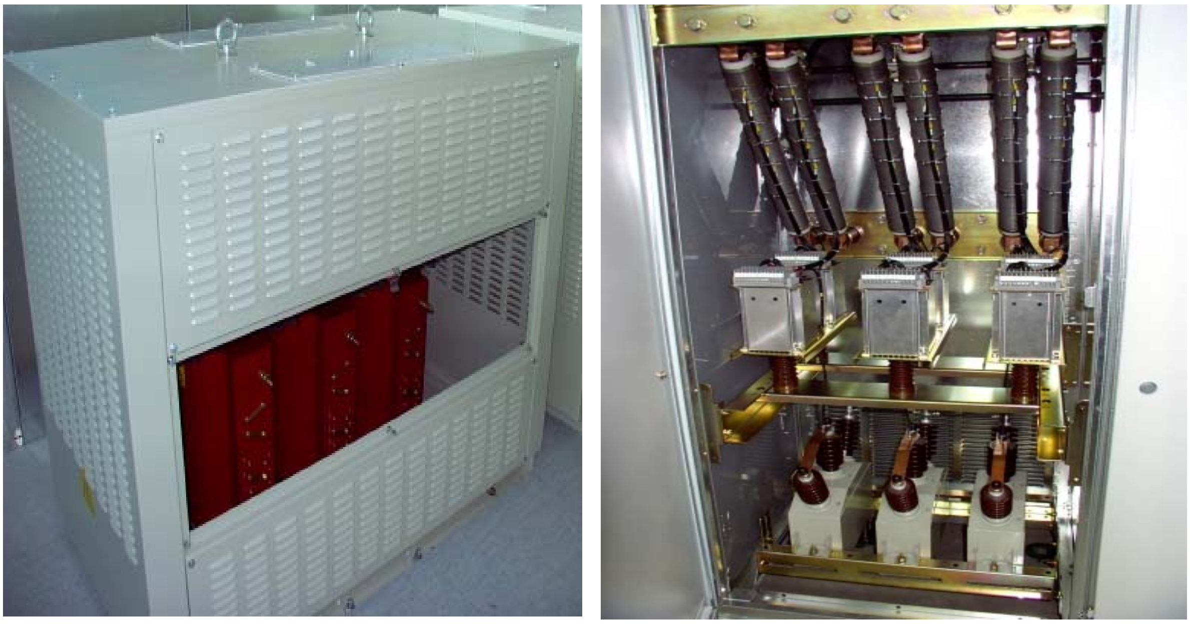


Fig. 31: **One of the transformers in security cage and a view of transmission line (consists of R,L,C elements)**

Description to ***Fig. 32***:

no.	facility	manufacturer	technical data
1	Diesel-SG set	Polyma	Diesel: 31.4kW, 1500min^{-1} SG: 3x400V Y, 50Hz, 32/38 kVA, cosphi 0.8, 46.2/54.9 A, 1500/1800 min^{-1}
2	Diesel-SG-inverter set	Kirsch/SMA	Diesel: 30kW, 2450min^{-1} SG: 3x400V, 50 Hz, PME 20kVA, 28.8 A nominal output of inverter: 3x400V, 50 Hz, 22kVA, 17.6kW, 32A speed range: 1200 - 3000 min^{-1}
3	DCM-SG set (grid simulator)		nominal output: 3x400V, 50 Hz, 80kVA, cosphi=0.8, 116A (currently not available)
4	Crossbar switch cabinet with supervisory control unit		
5	DCM-IG set (WEC simulator)		nominal output: 3x400V, 50 Hz, 5 kW; controlled by Siemens S5, connected to Interbus-S (IBS S5/SL-LB)
6	M-IG/SG set (mini grid simulator)	SMA	nominal output: 3x400V, 50 Hz, 15 kVA; extern controlled by analog current input
7.1	PV inverters (2x Sunny Boy 700)	SMA	nominal rating: each single phase 700 W
7.2	Battery inverter (3x Sunny Island)	SMA	nominal rating: each single phase 3.3 kVA, cosphi=1 (connected in star)
	Battery bank	BAF	14 kWh
8.1	PV inverters (1x Sunny Boy 700, 1x Sunny Boy 850, 1x Sunny Boy 2000)	SMA	nominal rating: single phase 700 W, 850 W, 2 kW
	Control unit (Sunny Boy Control)	SMA	
8.2	Battery inverters (3x Sunny Island)	SMA	nominal rating: each single phase 3.3 kVA, cosphi=1 (connected in star)
	Battery bank	Hagen	14kWh
8.3	Diesel-SG set	FG Wilson	nominal rating: 12.5 kVA, 10.0 kW; extern controlled by start/stop signal
9	10 kV Hardware network		3X100 kVA transformers, U_n=10kV/0,4kV,

no.	facility	manufacturer	technical data
	simulator		Phase group :YNyn0/Dyn5, I_n=5,77A/144,33A Three different T-equivalent circuits for modelling lines or cables maximum up to 20km for the lines and up to 10km for the cables
10	SINVERT solar hybrid system	Siemens	3x400V, 50 Hz, 30 kVA battery inverter, 20 kVA PV inverter, 34.5 kWh battery bank, contolled by Siemens S7
11	Three phase inverter	SMA	nominal output: 3x400V, 70 kVA
12	Central control and visualisation unit		
13	Battery bank		96 V
14	Virtual battery	ISET	95 V, 30 kW
15.1	Battery inverter (1x Sunny Island)	SMA	nominal rating: single phase 3.3 kVA, cosphi=1
15.2	PV inverters (2x Sunny Boy 850)	SMA	nominal rating: each single phase 850 W
16	PV inverters		various types of single phase inverters
17	CHP station	Senertec	nominal electrical output: 3x400V, 50 Hz, 5.5kW, 6.2kVA, cosphi=0.89, 9A
	Loads:		
	Ohmic load element	Ruhstrat	3x400V, 4.6 - 18.4 kW per phase +N, R_N=0.115 ohm, I_N=200A
	Ohmic load element	Ruhstrat	3x400V/230V, 100/2*200/500/1000/2000 W per phase, R_N=13.2 ohm, I_N=17.3A
	Ohmic load element	Ruhstrat	3x400V/230V, 100/2*200/500/1000/2000 W per phase, R_N=13.2 ohm, I_N=17.3A
	Inductive load element	Ruhstrat	3x400V/230V, 100/2*200/500/1000/2000 var per phase, L_N=42 mH, I_N=17.3A
	Capacitive load element	Ruhstrat	3x400V/230V, 100/2*200/500/1000/2000 var per phase, C_N=240 mF, I_N=17.3A
	other loads like refrigerators, lamps, pump drive, drilling and welding machine		

Tab.1 List of operational units in the DeMoTec Hall

Crossbar Switch Cabinet: Crossbar Switch Cabinet (***Fig. 34***, ***Fig. 33***) is controlled via Interbus-S controller. Special software makes possible to check the safety relevant conditions and to activate the electric grid if only these conditions are allowed. Controller is accessed via OPC server, it makes possible to visualize the state of switch cabinet and respectively to carry out switching operations. So, all switches on the ***Fig. 33***, which connect the plants to the DeMoTec Hall island grid, are situated in the crossbar switch cabinet and controlled via Interbus-S controller.

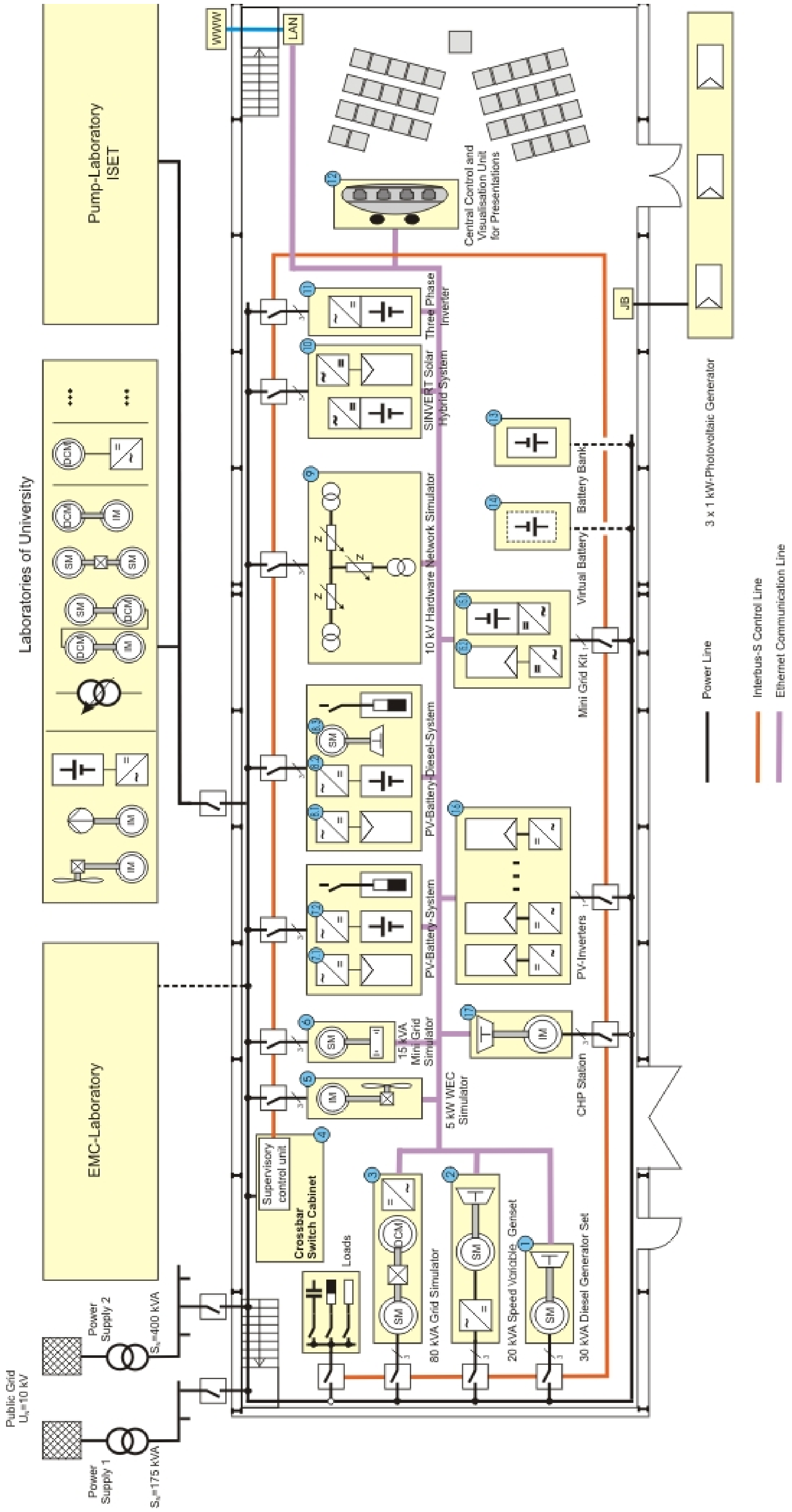


Fig. 32: DeMoTec Overview of Plants

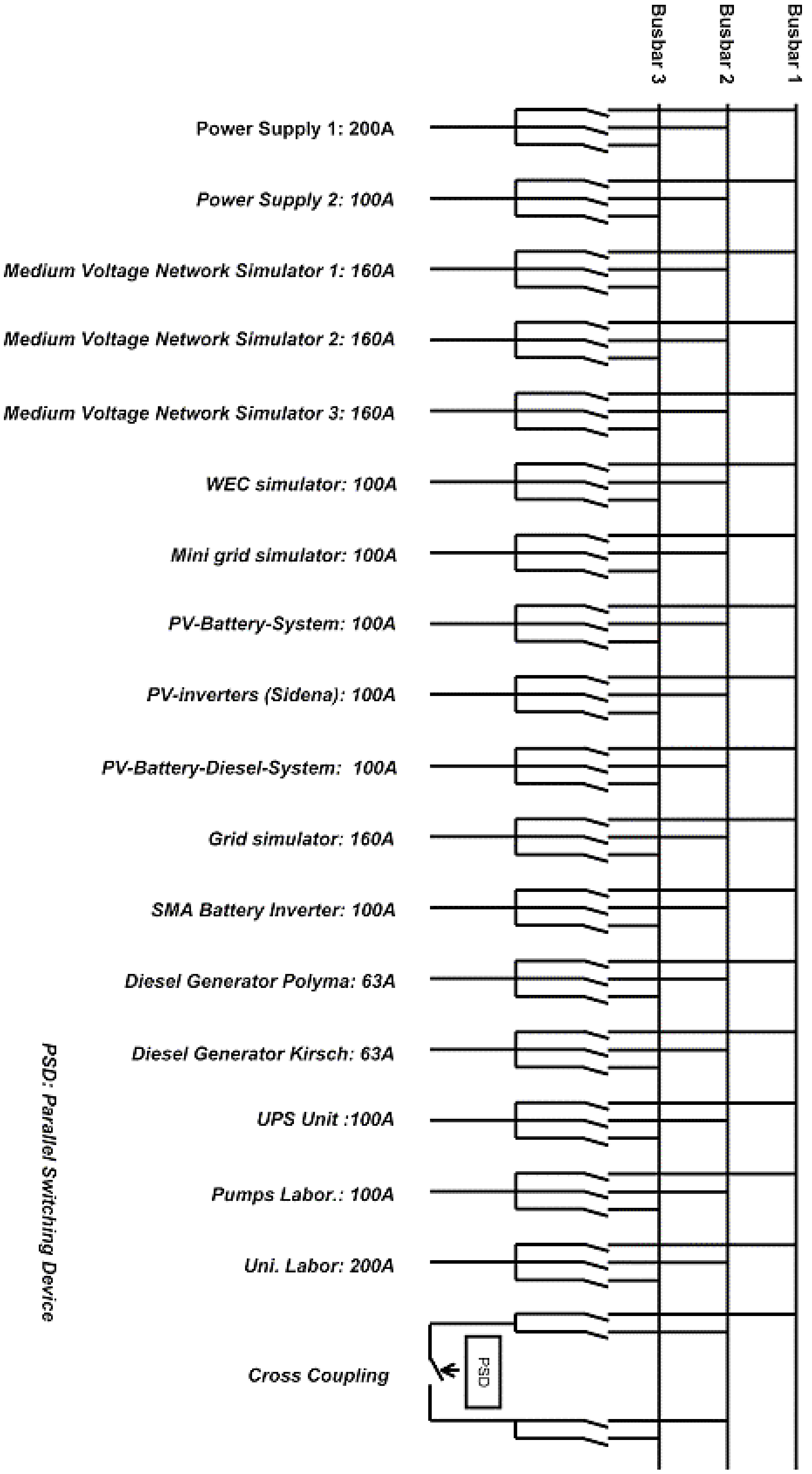


Fig. 33: DeMoTec Crossbar Switch Cabinet (low voltage side, single phase representation)

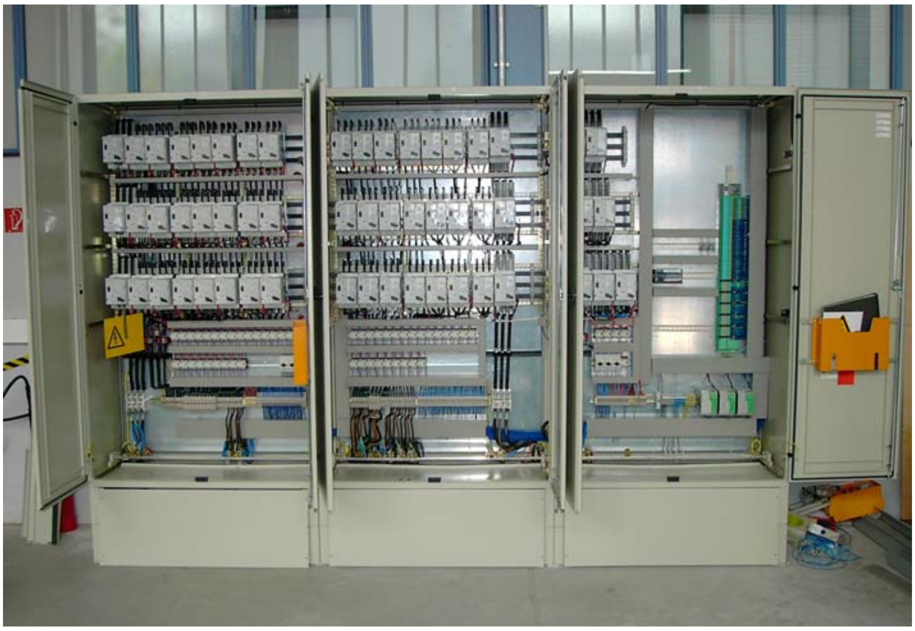


Fig. 34: Crossbar Switch Cabinet

SCADA system for DeMoTec

Overview

The Design Center for Modular Systems Technology comprises a variety of components related to energy generation, distribution, transmission, storage and conversion. The power range reaches from a few kW up to 200 kW. The interaction of these components within an electrical network is one of the main topics to be researched by ISET. This covers also the control of these components and therefore the exchange of data information in order to enable a safe, reliable and optimised operation.

Nowadays the exchange of information between components of different manufacturers in the lower power range (< 1 MW) is a problem due to a lack of standardised data exchange systems and protocols. These sophisticated systems (e.g. Profibus) and protocols (e.g. IEC 870-6 TASE.2) exist for larger units where the price of the communication system compared to the overall investment is low. Especially in the low power segment, a large variety of different, proprietary solutions are available. Besides that some components do not even have a communication interface.

In order to examine the interaction and control of components it is inevitable to interlink them on a common and easy programmable interface.
General characterisation of communication interface:

- vendor independent
- platform independent
- open
- rapid prototyping for laboratory purposes, but professional
- powerful in order not to be limited by e.g. bandwidth restrictions

Based on these characterisations an analysis of available communication platforms has lead to the use of TCP/IP over Ethernet, one of the most widespread technologies which is even gaining market shares in industrial field applications.
A SCADA system matching this concept will be installed in the DeMoTec within the year 2003.

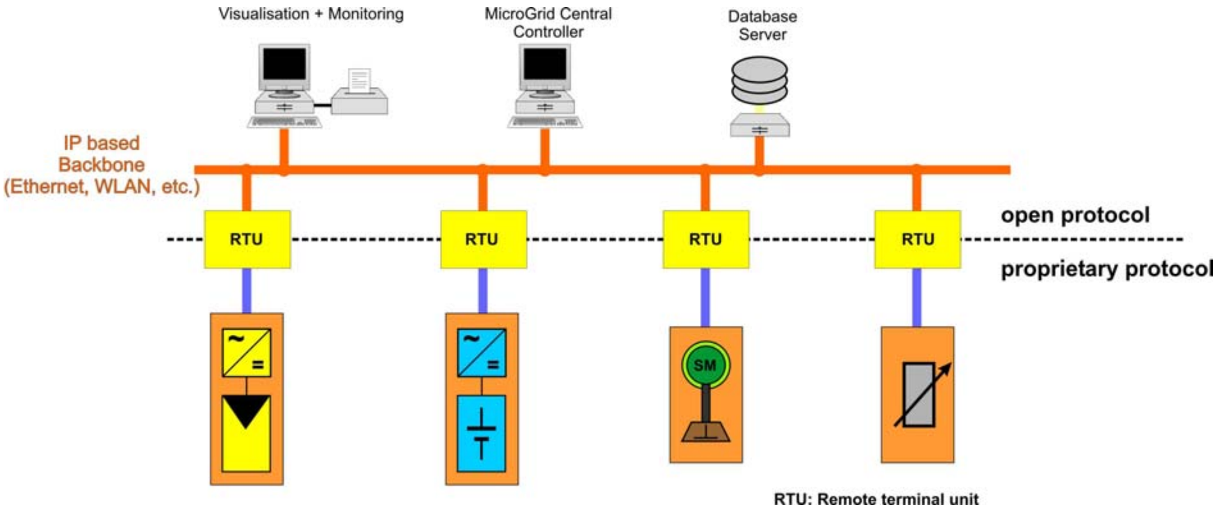


Fig. 35: DeMoTec SCADA system

In this system the communication backbone is being built by an Ethernet network. All components are linked to this backbone via remote termanial units (RTU). These RTUs will act as protocol converters translating vendor dependent protocols (e.g. SMAData from SMA Regelsysteme GmbH) into vendor independent XML-encoded data. Furthermore the RTUs can be programmed with additional control tasks.
Data collected by the RTUs may be stored in a SQL-database to which all necessary processes (e.g. visualisation, monitoring, supervisory control) have access.

Object model

A very simple object model has been used in order to simplify the creation and later analysis of communication telegrams. In principle the model consists of two object types, the device object and the channel object. Within a telegram these objects can appear multiple times, e.g. a telegram can contain information about 2 devices, each one with a different number of channels.

Fig. 36: Simple object model

Communication API

As a high level communication protocol the widespread XML dialect XML-RPC has been selected. It is available on many different platforms and provides the necessary functionality in order to develop a laboratory SCADA system.

XML-RPC is a Remote Procedure Calling protocol that works over the Internet.
An XML-RPC message is an HTTP-POST request. The body of the request is in XML. A procedure executes on the server and the value it returns is also formatted in XML.
Procedure parameters can be scalars, numbers, strings, dates, etc.; and can also be complex record and list structures.

Request example
Here's an example of an XML-RPC request:

```
POST /RPC2 HTTP/1.0
User-Agent: Frontier/5.1.2 (WinNT)
Host: betty.userland.com
Content-Type: text/xml
Content-length: 181

<?xml version="1.0"?>
<methodCall>
   <methodName>examples.getStateName</methodName>
   <params>
      <param>
         <value><i4>41</i4></value>
      </param>
   </params>
</methodCall>
```

```
<?xml version="1.0"?>
<methodCall>
 <methodName>DataRequest</methodName>
  <params>
   <param>
    <value>
    <array>
     <data>
     <value>
      <struct>
       <member>
        <name>Serial</name>
         <value><string>XXXXX</string></value>
       </member>
      </struct>
     </value>
     </data>
    </array>
    </value>
   </param>
  </params>
</methodCall>
```

Fig. 37: Example of XMLRPC encoded DataRequest telegramm

Remote terminal units

Hardware for RTUs are embedded PCs and microcontrollers containing Ethernet capabilities.
RTU for SMA hardware (Sunny Island, Sunny Central, Sunny Boy)
Specification of the device:
DSM Embedded Controller (Fig. 38)
VIA Eden 667 MHz processor, fanless, 128 MB RAM, 128 MB Flash Disk, RS 232, RS 485
Operating system: White Dwarf Linux (http://www.whitedwarflinux.org)
”White Dwarf Linux” is a special Linux distribution designed with respect to memory usage. A complete Linux system can be easily installed on a 16MB flash disk.

Fig. 38: Embedded Linux PC

Fig. 39: “three phase cluster inverter” with RTU at the DeMoTec

RTU for Loadcontroller, diesel gen-set, etc.

Fig. 40a: Dallas® Tini Board

The TINI is a very interesting little board from Dallas Semiconductor featuring an Ethernet interface, a 40 Mhz 8051 descendant (the DS80C390), up to 2 megs of non-volatile storage (flash and battery backed RAM) and numerous other interfaces (RS232/CAN/OneWire).
NETMASTER is a programmable controller based on a Dallas TINI module. It is inserted in a standard DIN 43880 enclosure and by its connectivity in network allows an easy integration with other systems. It uses a bi-processor structure (both core MCS51 compatible), the DS80C390 of the Dallas semiconductor used as central processor and the ADuC812 of the Analog Devices used as analog I/O manager.

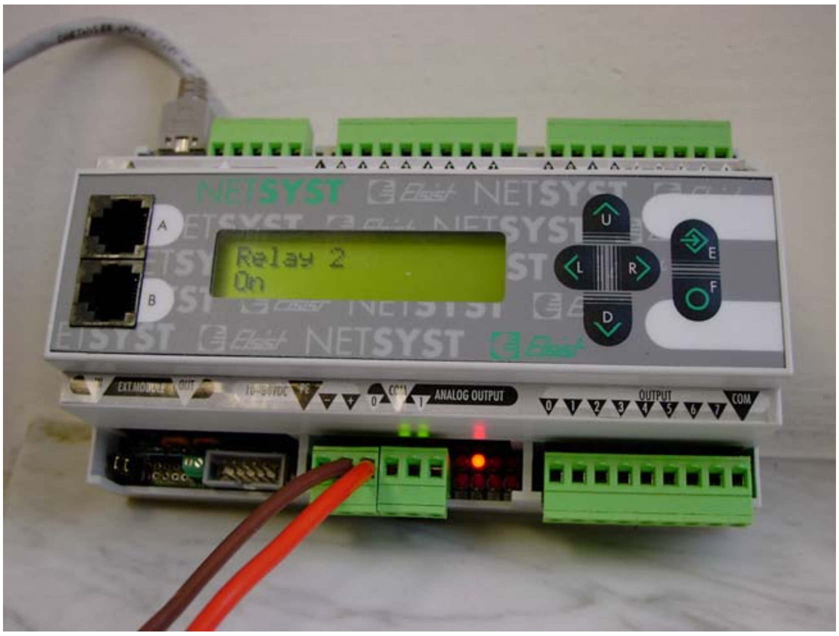


Fig. 40b: Elsist Netmaster

Features of Netmaster:

- 12 optoisolated inputs
- 8 relays logic outputs (or static)
- 4 analog inputs 0-10Vdc 12bit
- 2 analog outputs 0-2.5Vdc 12bit
- I/O status gauges (LED)
- Counter speed input
- Interrupt external input
- Ethernet interface
- CAN Bus or RS422/485 interface
- 1-Wire interface
- RS232C standard interface
- I2C interface for extension modules
- 512K FLASH memory, 512K SRAM memory with battery
- Real-Time Clock/Calendar
- 10-28Vdc power supply
- Keyboard 6 keys and LCD 2*16 alph. display (option)

The Netmaster is being programmed in Java.
As a first step an Ethernet enabled Loadcontroller has been developed.

Description of the Microgrid to be tested in the DeMoTec

In order to validate the different functions of a microgrid, a specific test configuration has been set up in the DeMoTec, which includes the following components:

- 4 grid forming units (2 battery units and 2 diesel generator sets)
- 2 renewable energy generators: PV and Wind
- several loads with different priority levels
- several automatic switches for sectionalizing the microgrid into up to 3 "low voltage" island grids
- supervisory control for a fully automatic operation of the microgrid (disconnection, re-connection, black-start, optimal dispatch)

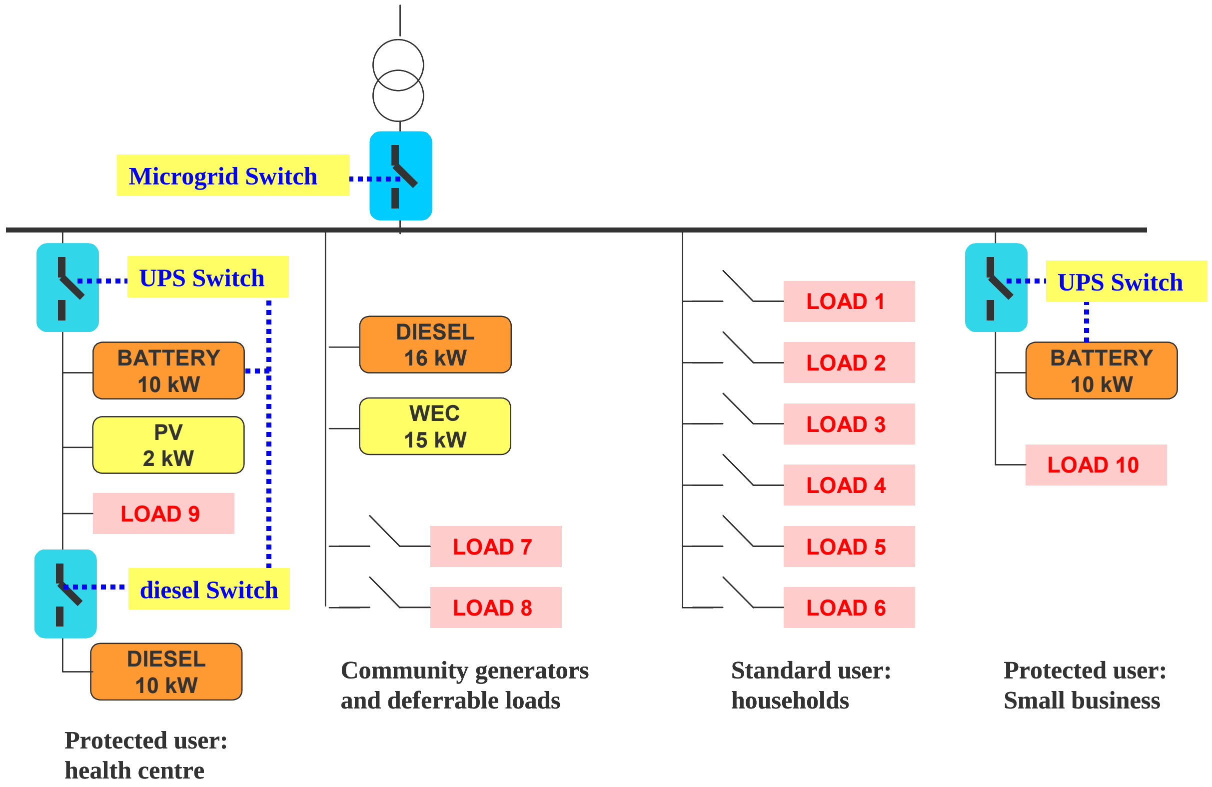


Fig. 41a: Microgrid test configuration

Using the above microgrid configuration, five tests are planned:

1. Transition from interconnected to island operation
    - TEST 1: high impedance fault on main grid
    - TEST 2: Microgrid overloaded by main grid
    - TEST 3: low impedance fault on main grid
2. Transition from island to interconnected operation
    - TEST 4: Re-connection to mains after fault
    - TEST 5: Microgrid black start

In order to perform the microgrid tests, additional DeMoTec infrastructure will be necessary as represented on the next figure. The test microgrid is connected to the main grid via the Medium

Voltage simulator, in order to include one 100 kVA LV/MV transformer at the point of common coupling. Additional loads, external to the microgrid are included for testing overload situations. External short circuit tests will also be tested.

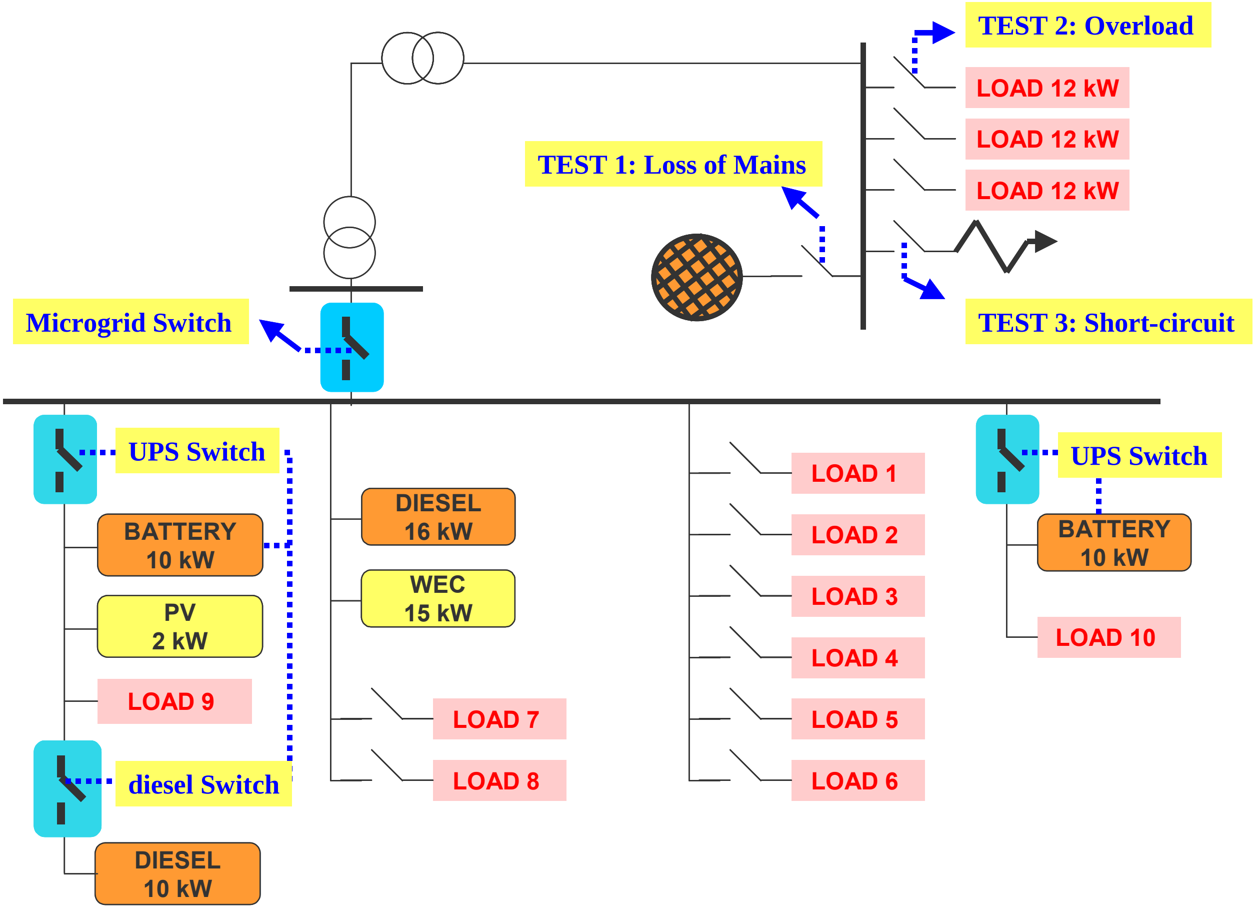


Fig. 41b: Microgrid fault testing configuration

The Communication infrastructure has been adapted to allow a multi-agent supervisory control system to be implemented. Several tests, including a secondary control strategy for the dispatchable units, have been performed successfully with the multi-agent software from Labein.

4 Test laboratory of Sunlight (Germanos)

System's description

The system is consisted from the following parts:

- Container 6,3 x 2.43 x 2.91m (***Fig. 41***,***Fig. 42***).
- Photovoltaic Panels (PV) of 3kW total peak output power (***Fig. 43***).
- Folding metal base for the PV Panels (***Fig. 43***).
- VRLA Lead-Acid Battery string, 48V, 2 X 24 cells (***Fig. 44***).
- Solar Charge Controller (***Fig. 45***).
- Single phase inverter-charger consisted from two parallel single phase inverters 4,5 kW each (***Fig. 46***)
- A 2,5 kWAir condition unit, in the battery's chamber (***Fig. 47***).
- A 10 kVA single-phase genset (***Fig. 48***).

Fig. 41: Container 6,3 x 2.43 x 2.91m (a)

Fig. 42: Container 6,3 x 2.43 x 2.91m (b)

Fig. 43: Photovoltaic Panels (PV) of 3kW total peak output power

Fig. 44: VRLA Lead-Acid Battery string, 48V, 2 X 24 cells

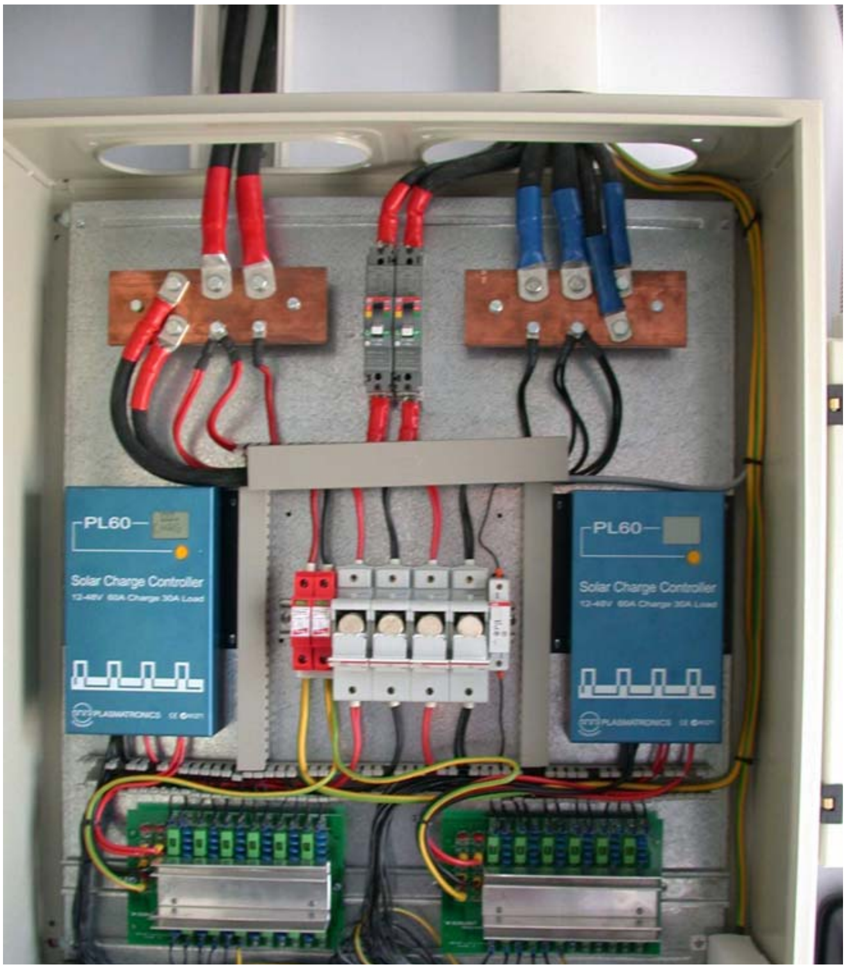


Fig. 45: Solar Charge Controller

Fig. 46: Single phase inverter-charger consisted from two parallel single phase inverters 4,5 kW each

Fig. 47: A 2,5 kWAir condition unit, in the battery's chamber

Fig. 48: A 10 kVA single-phase genset

All the necessary electrical and mechanical equipment are also included in the container (i.e. fuel tank, electrical switch-boards for dc and ac currents, fire extinguisher).

A graphical description of the system is given in ***Fig. 49***.

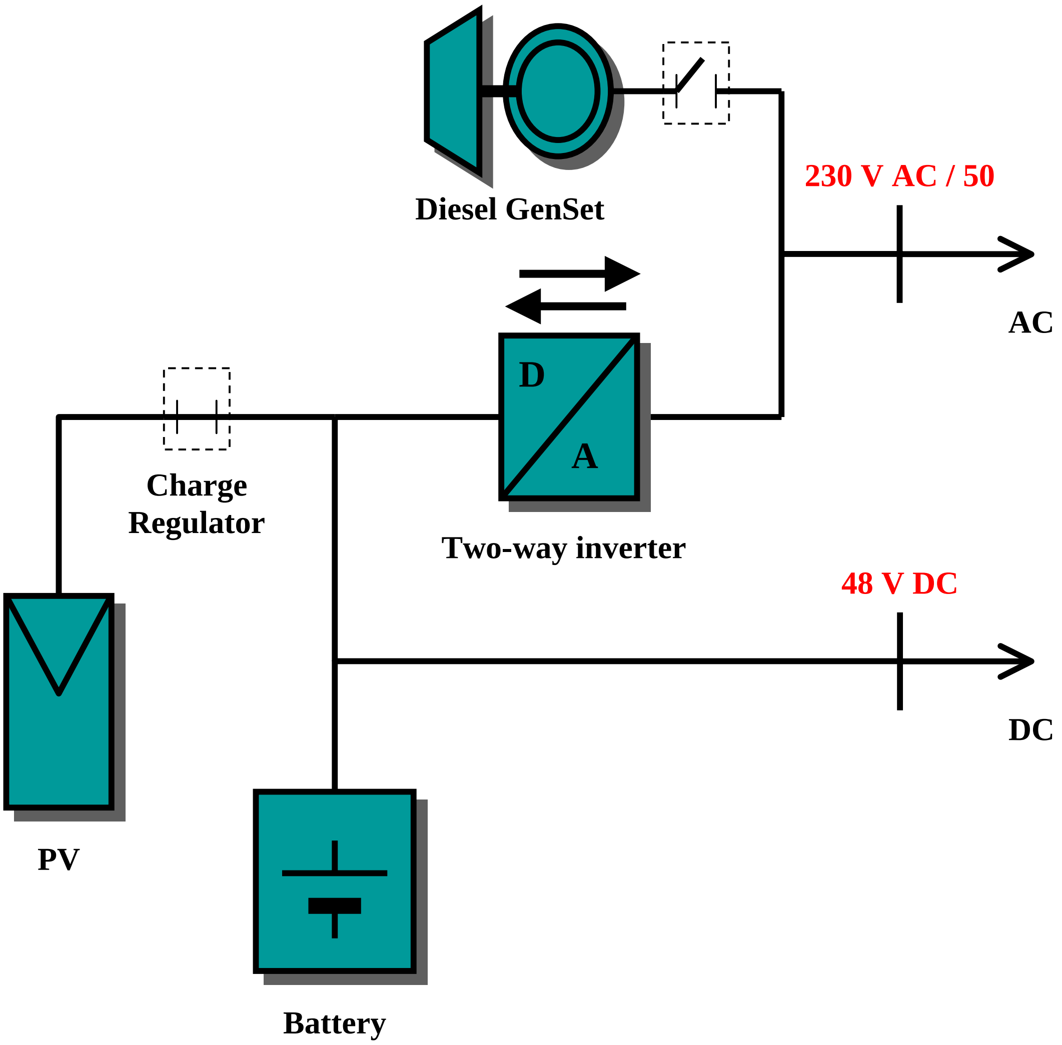


Fig. 49 Principal description of the system

5 Laboratory Microgrid (UMIST)

Work to date has focused on the design, build, commission and operation of the MicroGrid test hardware and control system. The test hardware design, otherwise known as a rapid prototyping system, required the combining of protection interfaces for the various sub-units, wiring schemes, cabling layouts, transformers, filtering and DC link capacitor arrangement design. Specification of the major sub-units is illustrated in ***Fig. 51***, and the layout of the AC:DC network side-inverter, it's wiring and control, are illustrated in ***Fig. 50***. To date all major components have been tested and commissioned, including the isolated generic measurement units for the voltage and current sensors. The advanced control systems used to control the Microgrid hardware have be designed, tested and verified in PSCAD/EMTDC.

The immediate work for 2005 has involved the development of control systems for real time control of the Microgrid hardware, using the Simulink/dSPACE control environment. A significant effort has also being made to produce concise documentation for the entire Microgrid hardware platform.

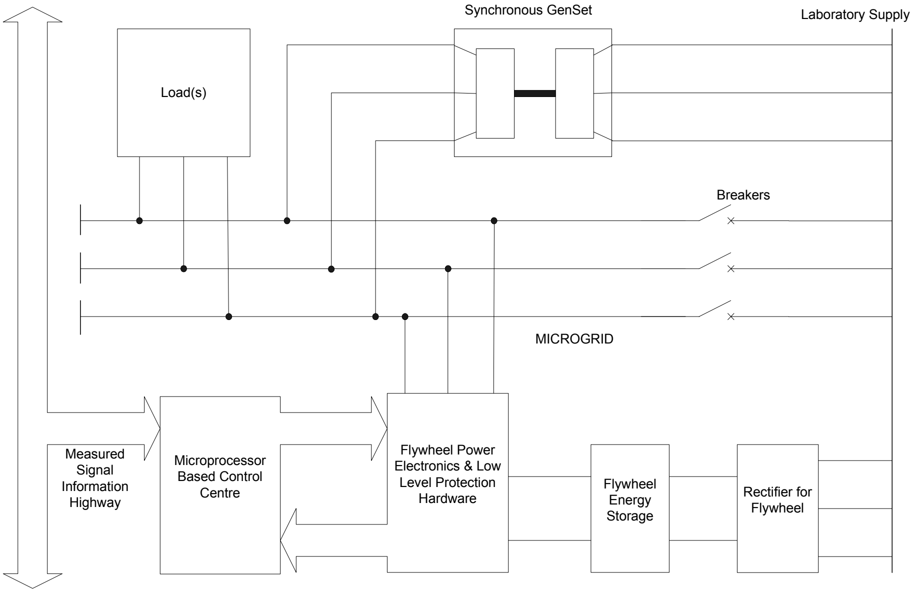
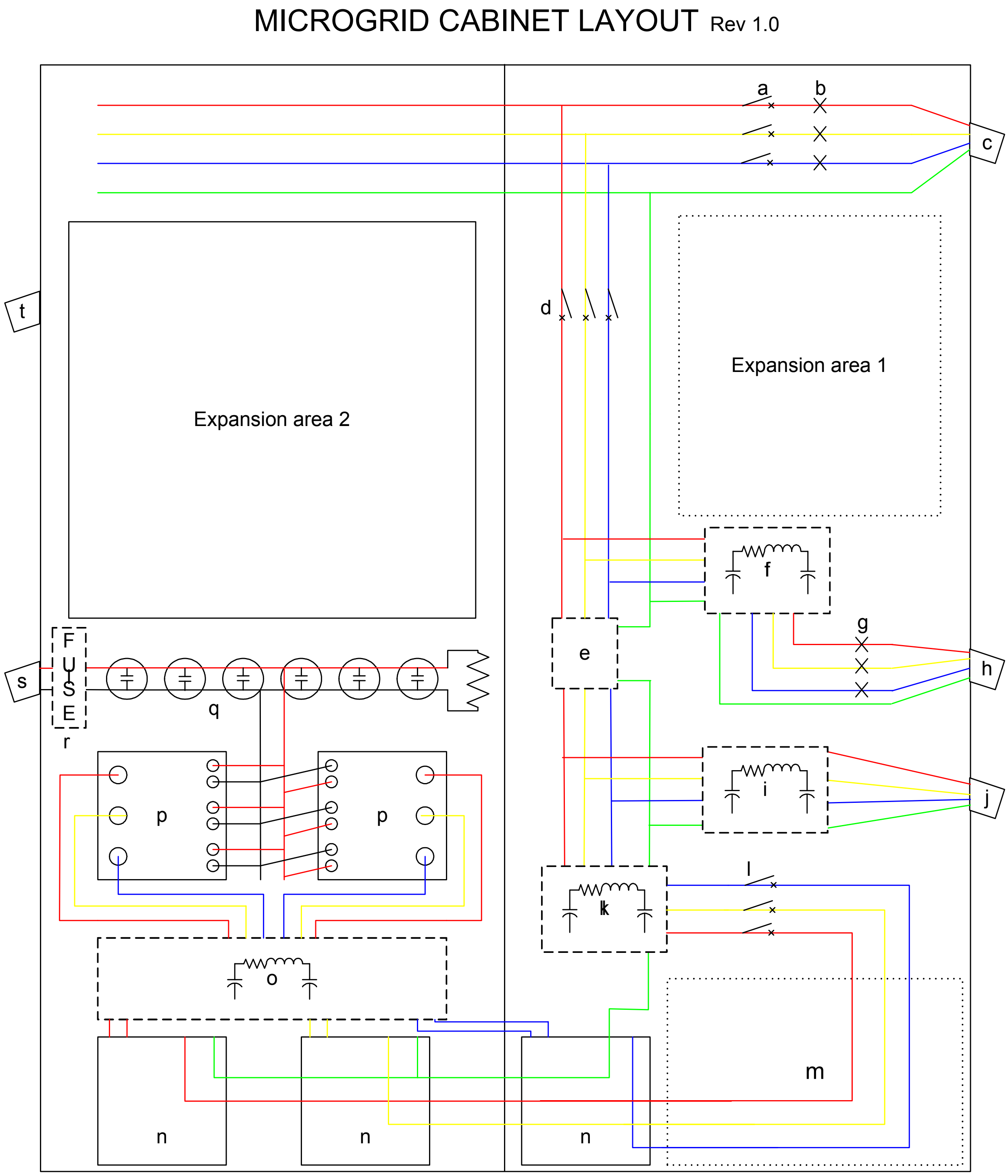


Fig. 50 MicroGrid Layout Schematic

Fig. 50 illustrates the hardware topology used in the UNIVERSITY OF MANCHESTER Microgrid/Flywheel energy storage laboratory prototype. The overall system is nominally rated at a 20kVA, although the flywheel and power electronics are rated much higher (100kW). ***Fig. 51*** illustrates the overall layout of the power hardware contained in the microgrid cabinet.

The design build and commission of the laboratory Microgrid hardware/flywheel energy storage system is now complete.



a : Contactor for supply fault generation
b : Breaker for supply
c : Laboratory supply representing the grid (in)
d : Microgrid contactor
e : Connection point for additional supply transformer
f,I,k : Connection area and shunt reactors plus line impedances
g : synchronous machine in, overload breaker.
h : Synchronous machine input connection
l : Flywheel inverter system contactors

m : Expansion area for additional supply transformer
j : Loads out
n : Inverter coupling transformers
o : Inverter filter arrangement
p : Inverter/IPM modules
q : DC link capacitors and resistor
r : Main DC fuse
s : DC in
t : Auxiliary supply in

Fig. 51 Grid-side AC:DC Inverter Layout

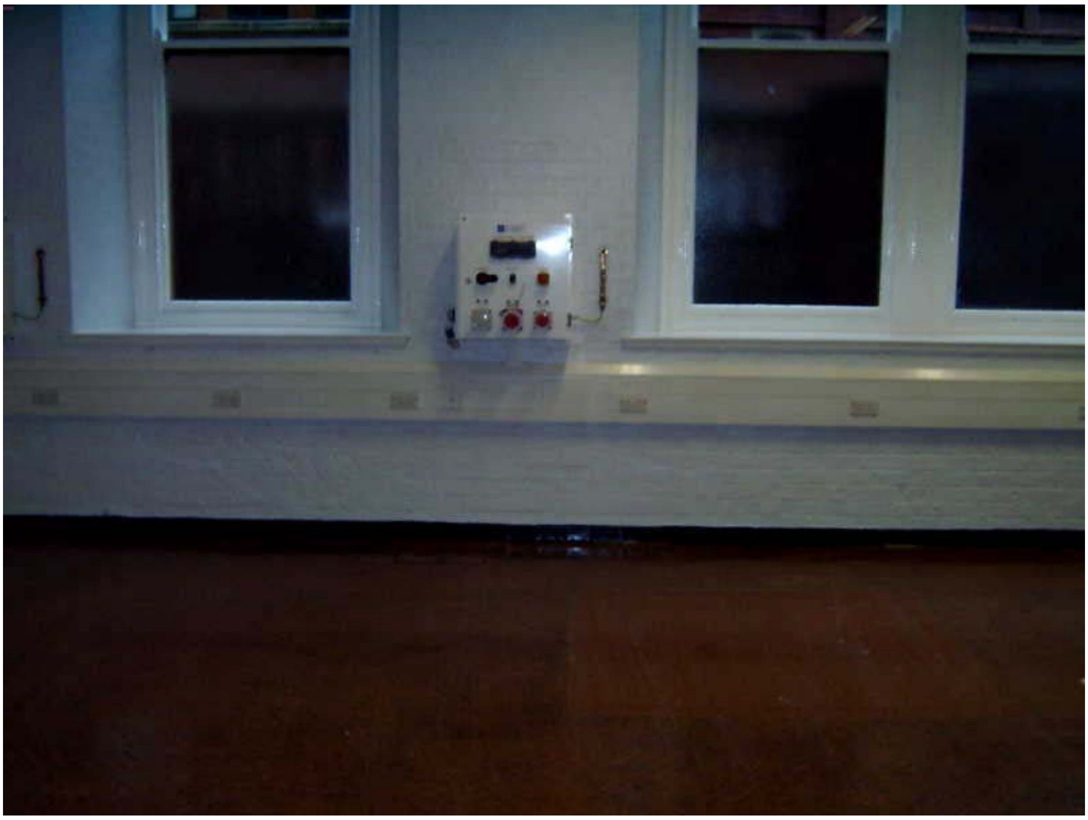


Fig. 52: August 2003 – Before hardware build

Fig. 53: May 2005 – Completed hardware

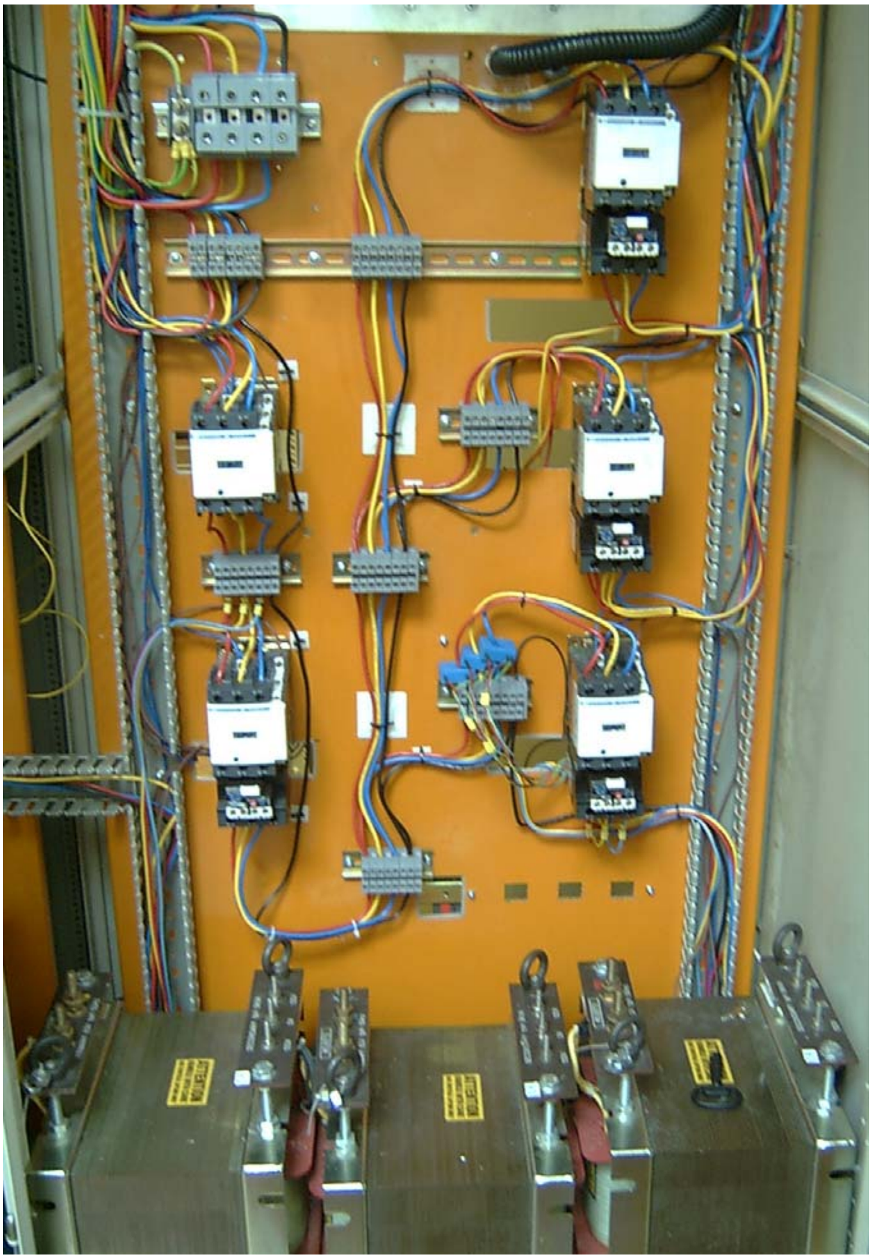


Fig. 54: **Mimic of a real microgrid, where various loads and sources are interconnected**

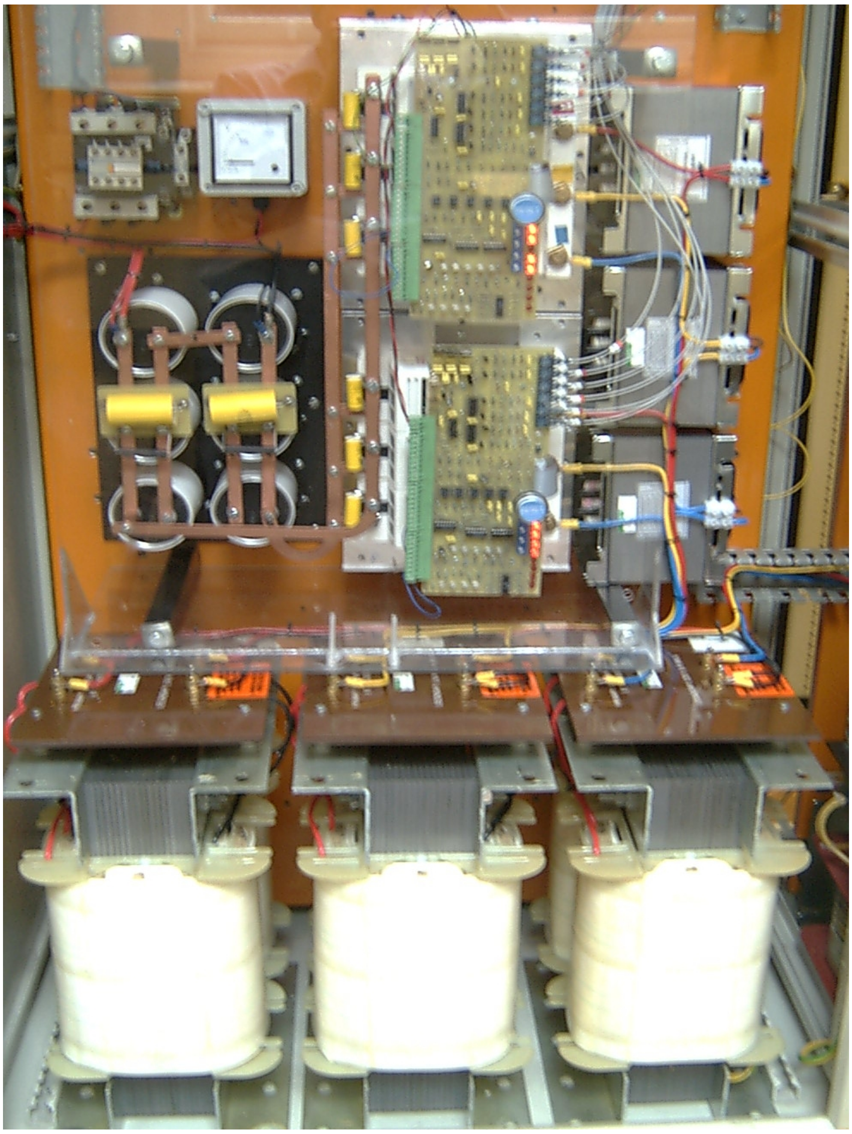


Fig. 55: Complete flywheel inverter system inc. connection transformers

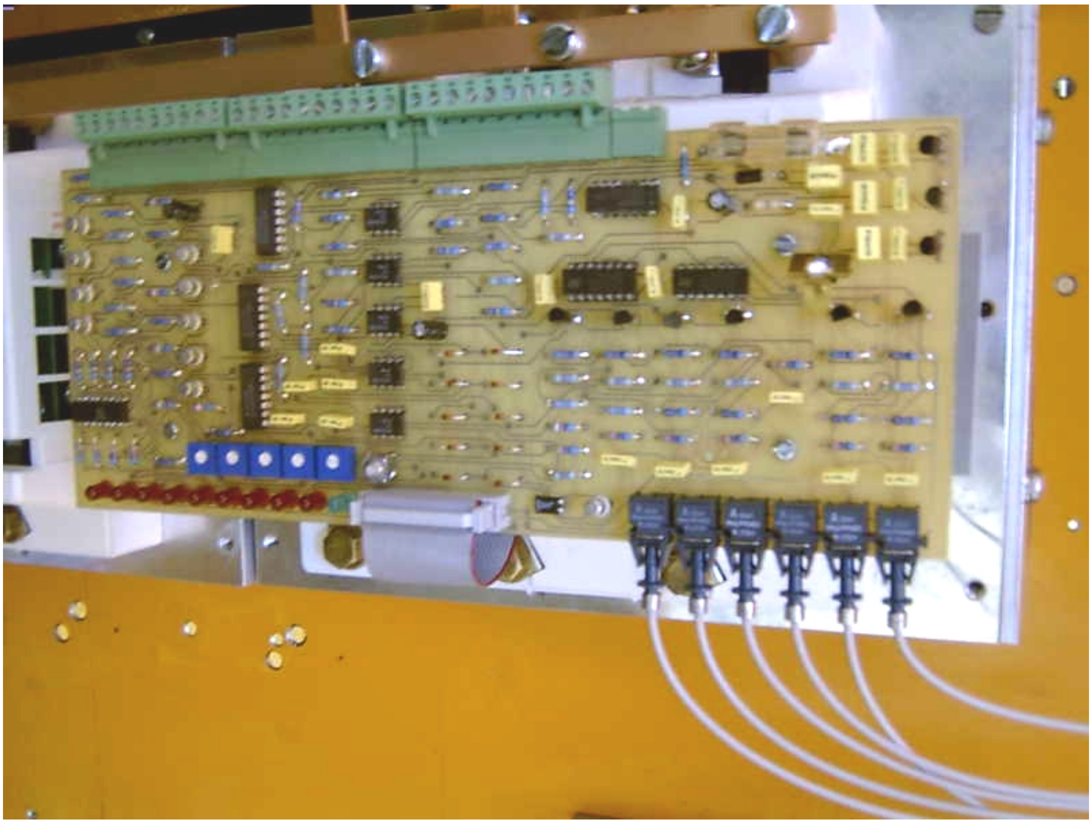


Fig. 56: IPM (Inverter) interface card

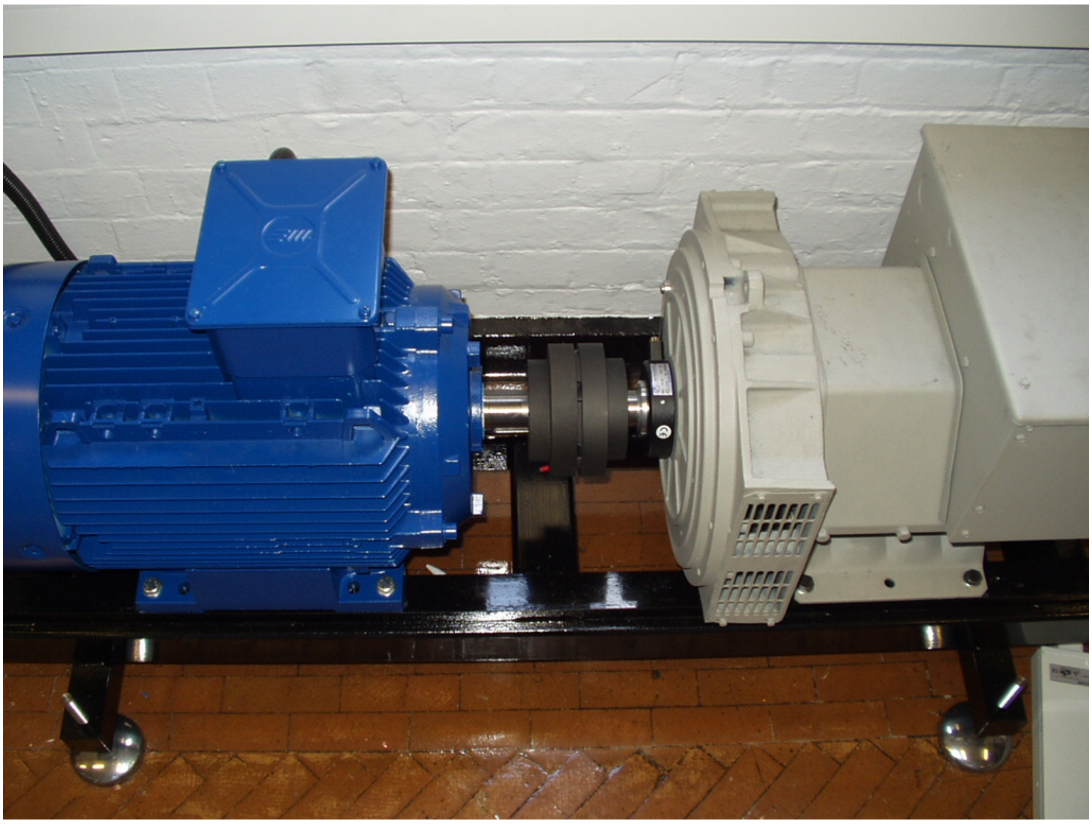


Fig. 57: 22kW Induction motor/Synchronous generator ‘microsource’

Fig. 58: 22kW AC motor drive

Fig. 59: 12kW load bank

Fig. 60: Inverter/flywheel DC power source (inc. dump resistors)

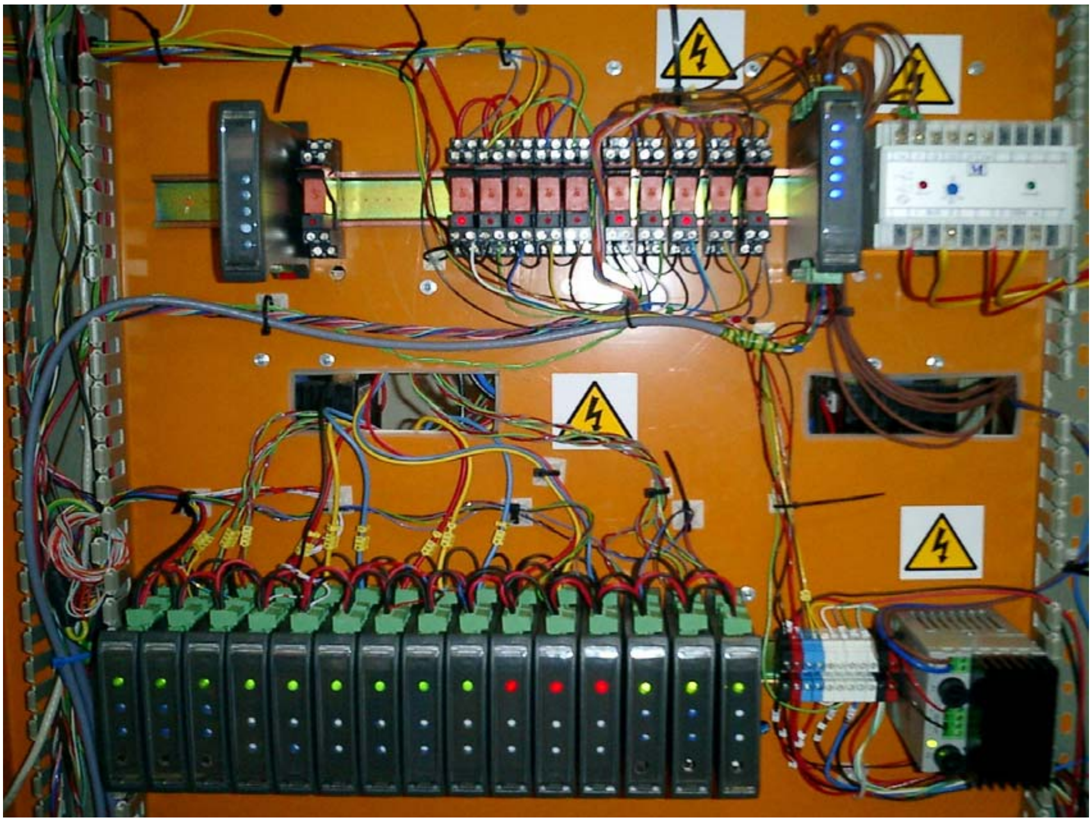


Fig. 61: Interface Modules

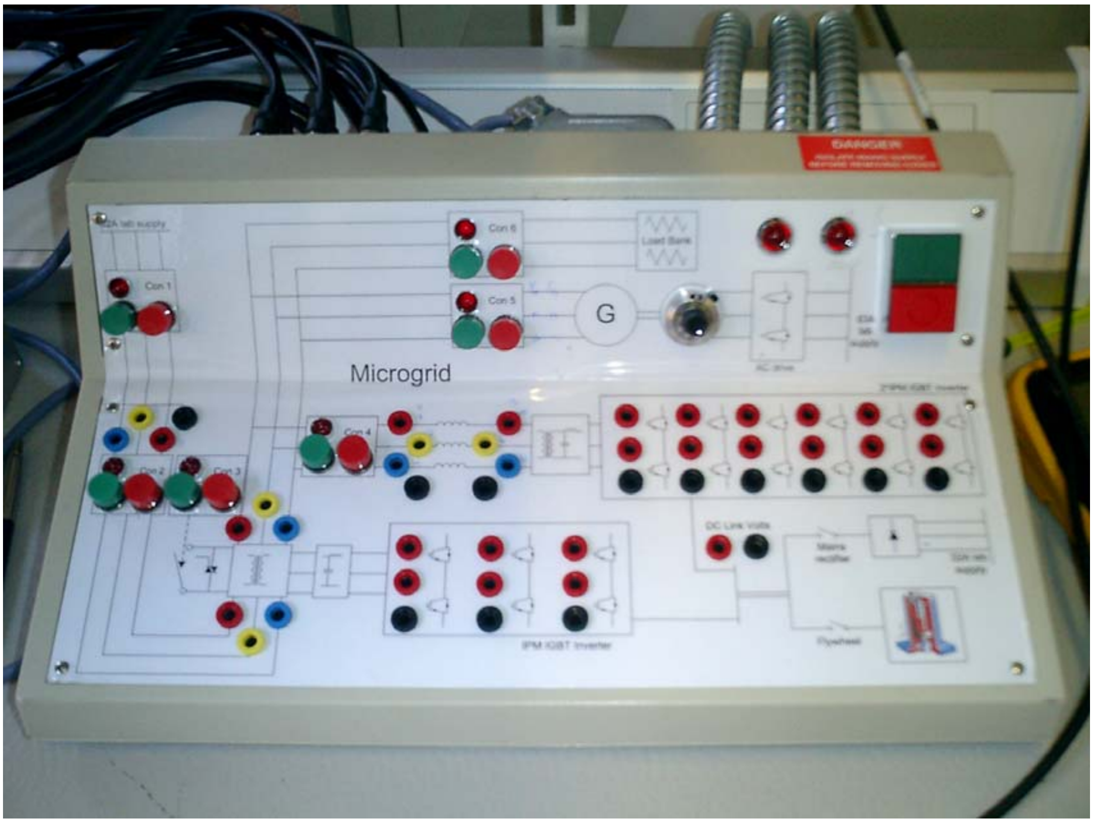


Fig. 62: Control Unit

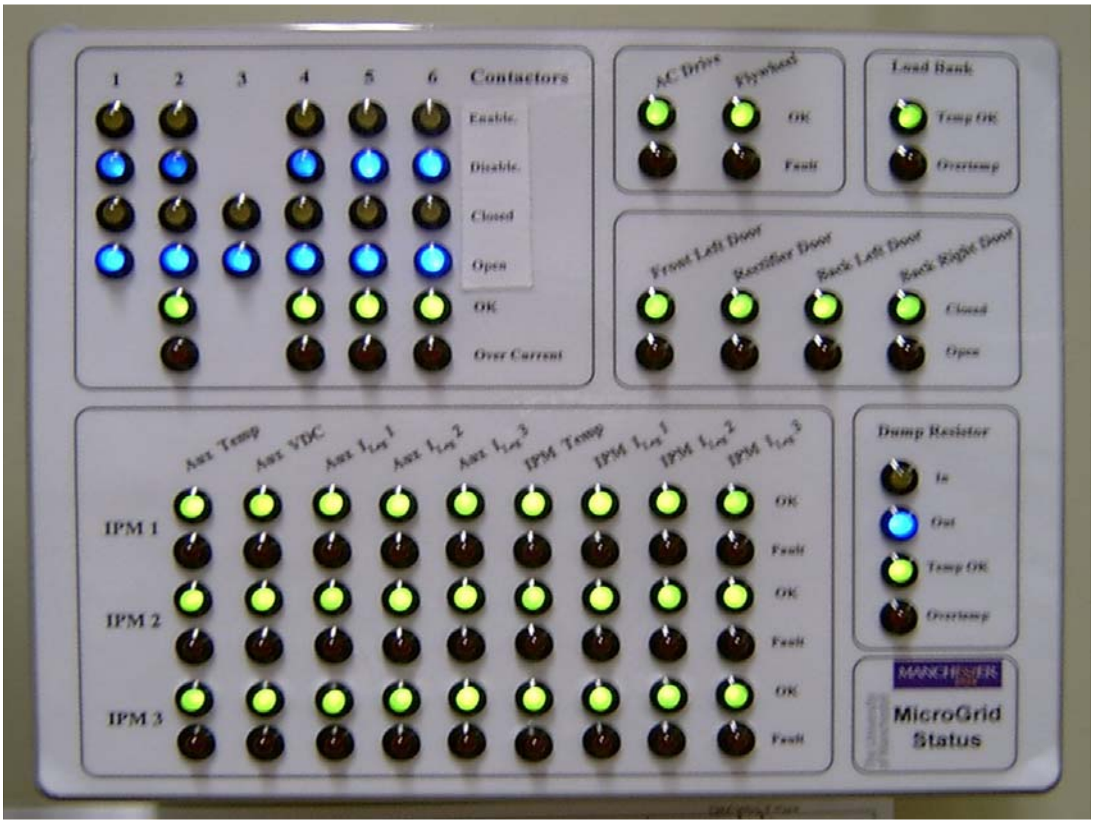


Fig. 63: Status Unit

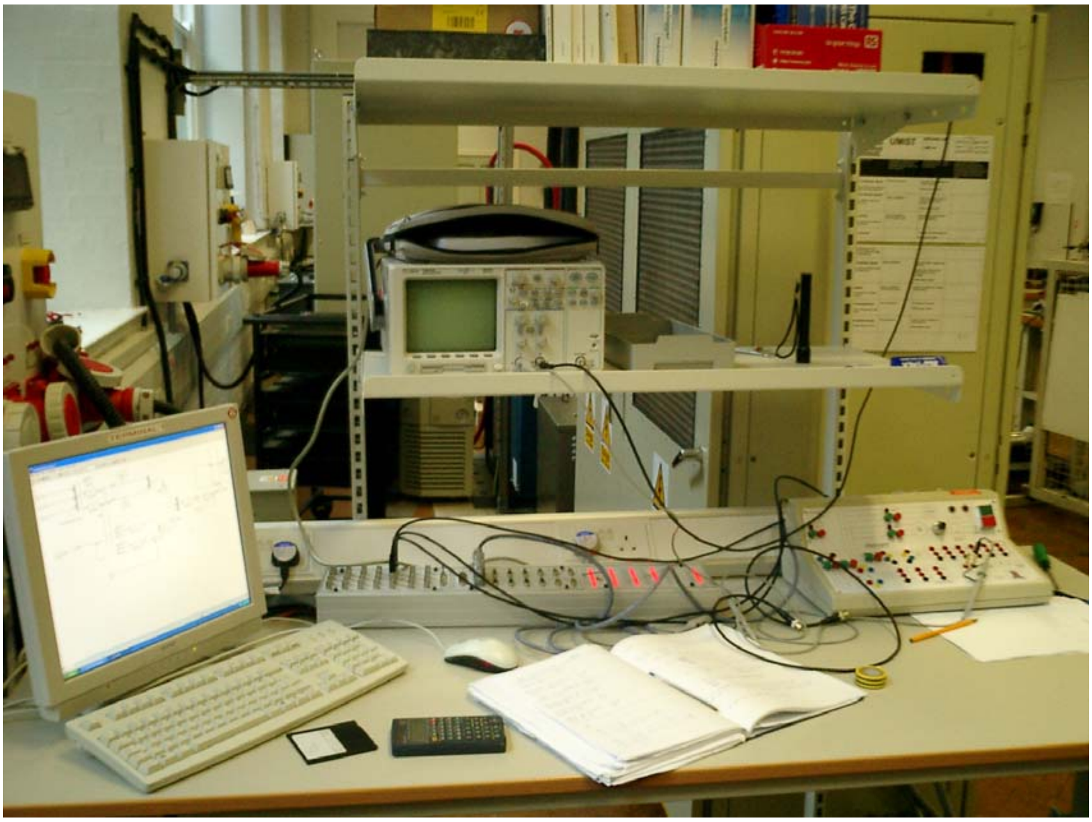


Fig. 64: Laboratory Microgrid control system

Figure	Caption	Description
Fig. 52	Hardware	Before development of the flywheel microgrid hardware system.
Fig. 53	Hardware	Completion of the design, installation and commissioning of the flywheel Microgrid hardware system.
Fig. 54	Microgrid	Mimics a real microgrid, where various loads and sources are interconnected. Variable impedances can be inserted in the wiring, so as to give a 'distance effect'.
Fig. 55	Flywheel inverter system	The visible twin IPM units convert the DC power supplied from the flywheel into Ac power for distribution in the microgrid. The three visible inverter-coupling transformers are of the single-phase type and are rated at 8kVA each. These units have been specifically designed to handle line to ground primary voltages in excess of 230Vrms (which can occur during reactive power control). The primary function of the transformers is to provide isolation between the power electronics and the microgrid. The visible inverter coupling reactors units are designed to work in conjunction with the IPM inverters and coupling transformers. They are the primary means of generating real and reactive power.
Fig. 56	IPM (Inverter) interface card	A University of Manchester designed and built IPM Inverter interface card. This card converts gate drive signals sent over six fibre optic links to electrical pulses. The card is capable of returning nine fault levels from over current, through to over temperature. The card also returns five fully isolated and buffered analogue signals that can be used to determine the state of the IPM and easily interfaced to a control system.
Fig. 57	Induction motor/Synchronous generator	The inverter driven synchronous generator is used to represent a microsource in the microgrid hardware system.
Fig. 58	22kW AC motor drive	The drive is used to control the 22kW induction machine, which forms a part of the microgrid. The drive can be configured to utilise droop control in necessary.
Fig. 59	12kW load bank	This has been designed to be capable of sinking 12kW of power. This unit represents a simple 'microload' connected to the microgrid.
Fig. 60	Inverter/flywheel DC power source	This unit was designed and built in house specifically to provide the flywheel with a variable DC voltage for various start-up procedures. The rectifier also supply's a DC link voltage to the IPM units. Once the flywheel is fully up to speed this unit can be disconnected, with the IPM units taking over power flow to and from the flywheel.
Fig. 61	Interface modules	In order to interface any measured signals to the control system, a set of voltage and current transducers have be designed. The units are housed in ABS rail boxes for ease of installation and reusability. The voltage units can provide up 1kV of isolation and the current devices pure galvanic isolation. Modules have also been designed tested and commissioned which allow the dSPACE control system to automate the normally manual operations performed on the hardware
Fig. 62	Control unit	The Control unit is the main interface between the dSPACE control system and the Microgrid Hardware. The Control unit also acts as a human interface with the hardware.
Fig. 63	Status unit	The Status unit allows the operators of the Microgrid hardware to quickly determine the state of the system.
Fig. 64	Microgrid control system control screen	This picture illustrates the dSPACE interface, which is used to control and monitor the operation of the complete University of Manchester Microgrid system. The PC control hardware is also used as the UPT flywheel interface, which can be used to control or monitor the operation of the flywheel

Table 1.1 Description of figures

6 Laboratory Microgrid (ARMINES)

Introduction

Thereafter is presented the Armines Laboratory Microgrid, installed at the Center for Energy & Processes of the Ecole des Mines de Paris (Sophia-Antipolis, FRANCE), according to Work Package H of the MICROGRID Project.

The microgrid consists of a manually configurable single-phase AC electric network (230VAC/50Hz), and of fully PC-controllable sources and loads. DC generators are connected to AC grid via appropriate and presently commercialized DC/AC power converters. Operation in either stand-alone or interconnected-to-the-LV-grid mode will be possible. Attention has been focused on the upgradability of the system.

Following paragraphs provide technical description for both the “hardware” and “software” parts, and propose a concrete case study as a benchmark for the software part of the microgrid and for different energy management strategies.

MicroGrid System Overview

The table and figure hereafter (Table 1.1, Figure 66) describe the main components of the microgrid system.

Components Type	**« Components »**	**Description**	**Figure n°**
AC voltage source	Local LV grid	Controlled interconnection to the LV grid (EDF).	
AC voltage source	Diesel generator	Genelec 4500MD. Diesel-fuelled, single-phase generator with remote start terminal and standard current-voltage control. Nominal power: **3,2kW** at 3000 rpm.	Figure 68
DC source	Battery	24 lead-acid elements, nominal voltage 2V, C_{100}=390Ah. Total nominal voltage 48V. Total capacity **18,7kWh**.	Figure 73
DC source	Photovoltaic (PV) generator	68 modules Photowatt BPX 47-451A, nominal Peak Power 45Wp each. Total nominal peak power **3060Wp**. Mounting tilt angle 45° (fixed, ≈ latitude of installation location).	Figure 67
DC source	Fuel cell (**future**)	Ballard 1,2kW.	
Inverter/Battery Charger	Trace SW4548E	Trace SW4548E from Trace Engineering Company. Bi-directional sine wave inverter. Maximum power **4,5kW**. 2 operating modes: “grid-forming” or “grid-following”, 2 AC inputs for grid-forming elements, 1 DC input for PV generator and battery, 1 230VAC/50Hz AC output. 3 relays dedicated to connection/disconnection of PV modules, and 2 relays providing start and stop signals for the fuel generator.	Figure 69
Current-source Inverter	**2** SMA Sunny Boy SWR850 (“Sunny Boy 1” & “Sunny Boy 2”)	String Inverter for PV plants. Current source (“grid-following” operation only). Maximum Power Point Tracking. Input voltage range 125-250VDC. Nominal output power **850W**. Automatic mains disconnection in case of grid disconnection for safety.	Figure 70
Inverter	Inverter for fuel cell	**to be defined**	
Resistive Load	**4** variable resistive loads. (“R1” “R2” “R3” & “R4”)	**0~1,5kW, step 100W**. Built with power resistors.	Figure 72
Resistive Load	**1** incandescent lighting load (“R6”)	**0~3,825kW, step 15W**. Built with incandescent lamps	Figure 71
Non-linear Resistive Load	**1** non-linear variable resistive load (“R5”)	**0~1,5kW, step 100W**. Built with power resistors and a single-phase thyristor bridge (controllable delay angle).	Figure 72
Inductive Load	**1** inductive load (“L”)	Nominal reactive power **0~1,4kVAr.** Temporarily up to 5kVAr. Continuously variable.	Figure 74
Capacitive Load	**1** capacitive load (“C”)	Nominal reactive power **0~-2,1kVAr, step – 33VAr.**	Figure 72
Induction Motor Load	**1** single-phase induction motor	Nominal Power **1,1kW.** Variable & controllable load torque.	
Grid	**12** transmission lines	Resistance 0,1Ω~1Ω Reactance 0,01Ω~0,667Ω	Figure 75
Grid	**1** Transformer	Ratio **1.** Nominal apparent power **1600VA**.	

Table 1.1 : Main components of the microgrid

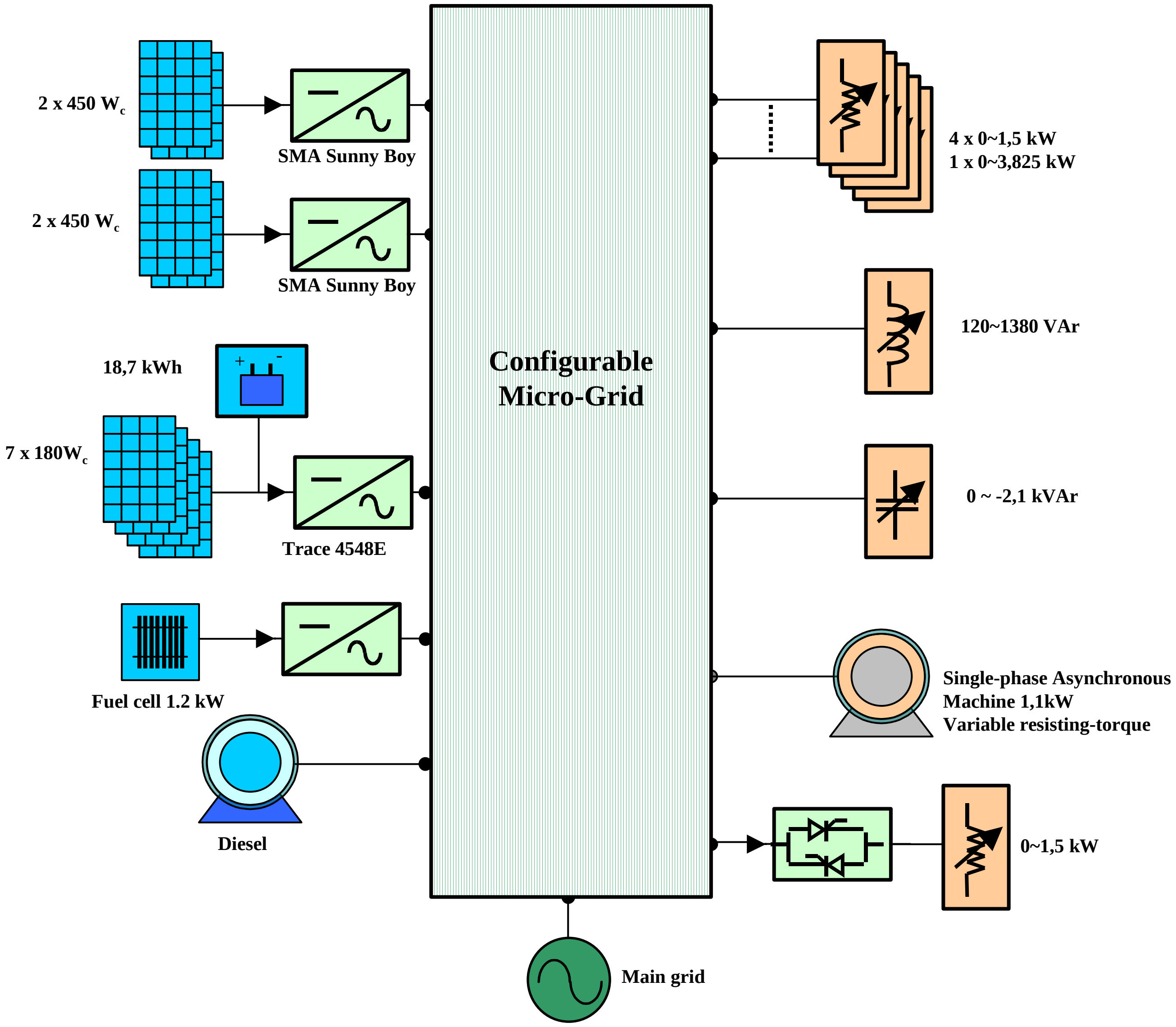


Figure 66 : Global description of the Armines microgrid system


Figure 67: Photovoltaic generator


Figure 68: Diesel generator with its fuel tank


Figure 69: Trace SW4548E inverter

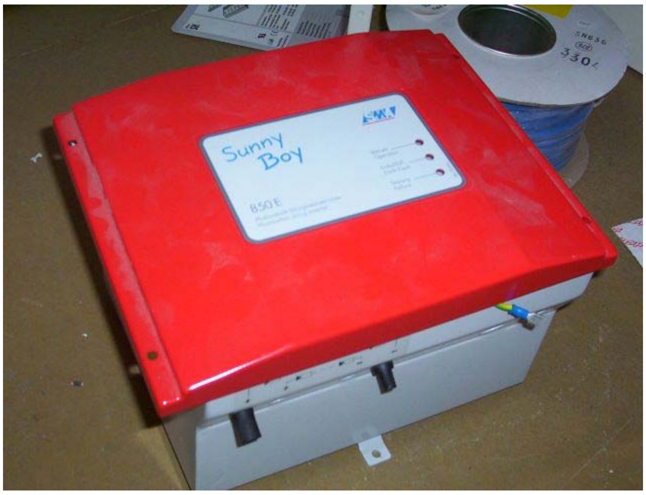


Figure 70: SMA Sunny Boy inverter

Figure 71: Incandescent lighting load

Figure 72: Resistive and capacitive loads

Figure73: Battery with shunt resistors and temperature sensors

Figure 74: Inductive load

Figure 75: Transmission lines

Hardware description

The control of the system is performed by the PC through relays: connection/disconnection of loads and sources, control of load values…

Main cabinet

The different components are physically dispersed in the laboratory, but control, visualization and system topology configuration are centralized for the user in a single cabinet (*main cabinet,* Figure 76).

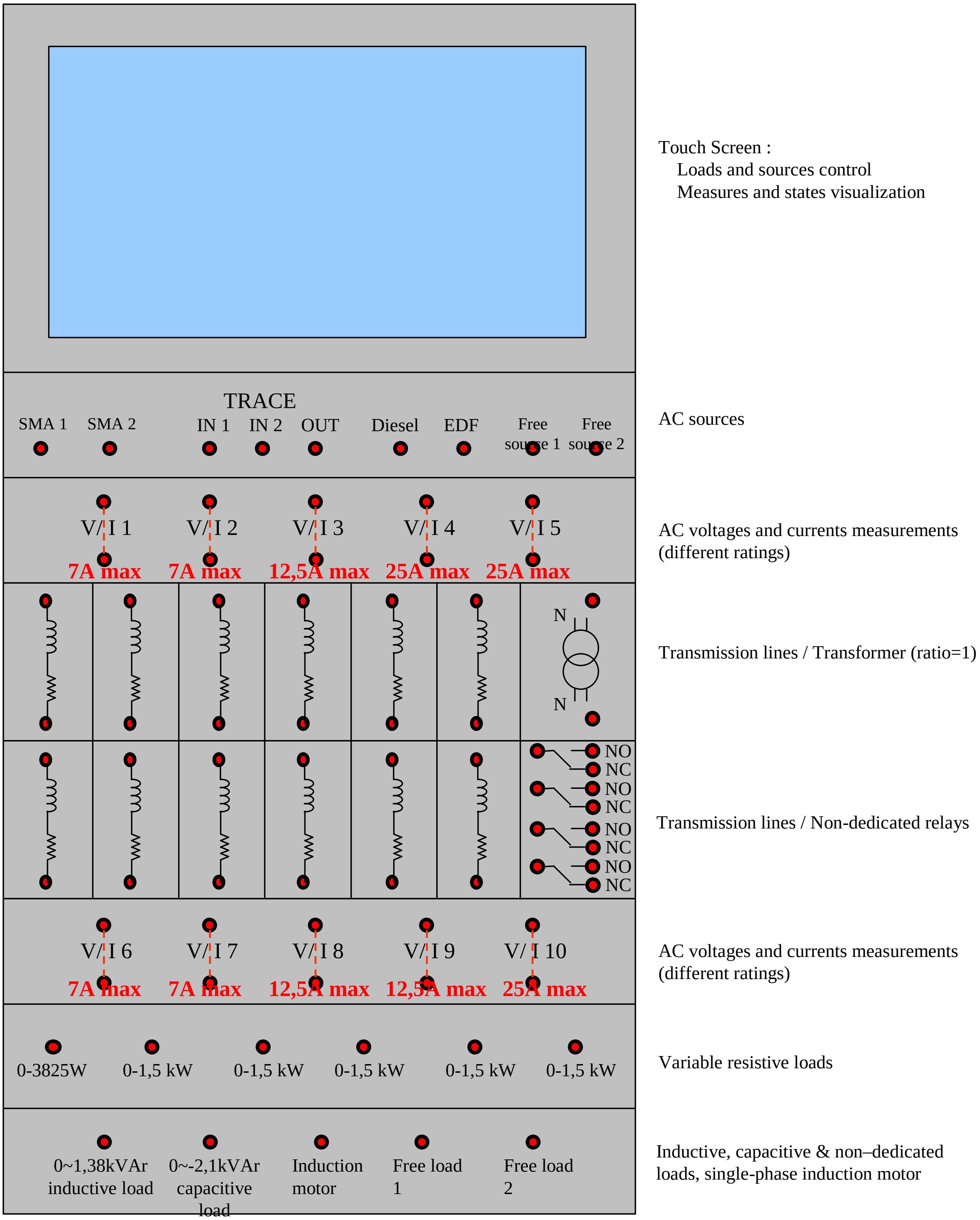


Figure 76 : Front Face of the Main Cabinet

Note: Emergency stop is not represented here.

The touch screen is the interface between the system and the user: it allows control & visualization of data displayed by the software. The user can interact with the system by pressing buttons on the screen.

The main cabinet also gives access to the system topology. The user can connect sources to loads through the transmission lines (via AC measurements if necessary) with electric cables, therefore defining the system topology manually. One phase only is accessible to the user, neutral conductor is common for all AC elements.

2 free source plugs and 2 free load plugs are provided to extend the possibilities of the system, as well as 4 undedicated relays (e.g. simulation of a transmission line defect).

Different ratings on the AC measurement channels have been decided for better resolution.

Nominal current for all the system is maximum 25A, corresponding to 5750VA (under nominal voltage 230VAC).

Photographs below show the realization of the main cabinet (Figure 77,Figure 78).

Figure 77: Wiring of the main cabinet (under construction)

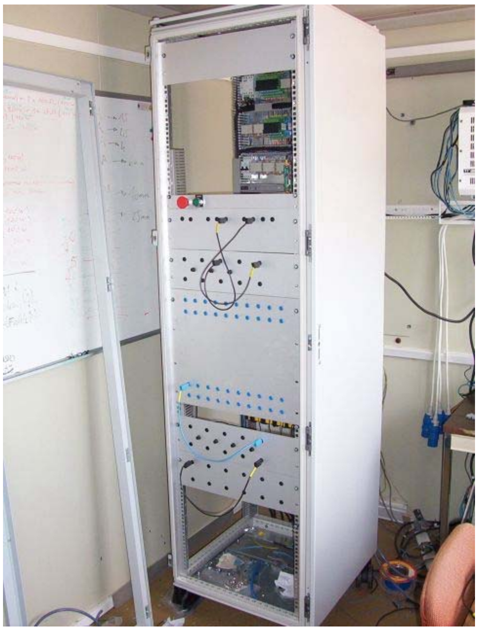


Figure 78: Front face of the main cabinet (under construction)

PV generator dispatching

A circuit has been developed to allow user to dispatch PV generators production either to the Trace or to the Sunny Boy inverters, respecting nominal input powers and voltages.

PC/system interface: the Multifunction Switch/Measure Unit AGILENT 34980A & modules

Relay control and retrieving of measurement data to PC is performed by the multifunction switch/measure unit AGILENT 34980A (Figure 79) including the following modules:

- One 34950A 64-channel digital I/O module (5V/30mA source or sink), used to drive 64 relays,
- One 34952A multifunction module with 32-bit DIO & 2-channel D/A, used to drive 32 relays, the delay angle of the thyristor bridge and the load torque of the induction motor,
- One 34921A 40-channel multiplexer switch module, used to multiplex signals to the 34980A’s internal DMM (electrical measurement capabilities).

Figure 79:Switch/Measure unit 34980A

Considering the maximum source current of the digital outputs, secondary static relays are used to drive the 12VDC power relays, as shown Figure 80.

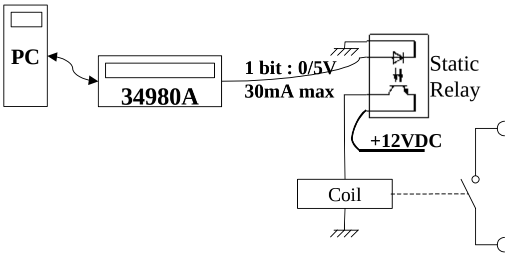


Figure 80: Relay control

Instrumentation

User has to be provided information on different voltages and currents, as well as active and reactive powers in the microgrid, for the system's observation and for its supervision.

The following measures are performed on the system:

- DC voltages and currents:
  - battery,
  - DC inputs of the 3 inverters,
- 10 channels for AC measurements (RMS voltage, effective current, phase displacement between voltage and current),
- meteorological measures: 3 insolation (Figure 82) and 4 external temperatures measurements,
- 2-channels oscilloscope for waveform visualization,
- temperature measurements on battery (useful to determine the state of charge of the battery),
- detection of the Trace's relays position.

DC and meteorological measurements are performed by the 34980A unit (directly for voltage, through shunt resistors for current, and through transducers for temperature and insolation).
AC measurements are multiplexed to a single electrical network analyzer ARDETEM EVA2501 (Figure 81), communicating its measures to the 34980A.

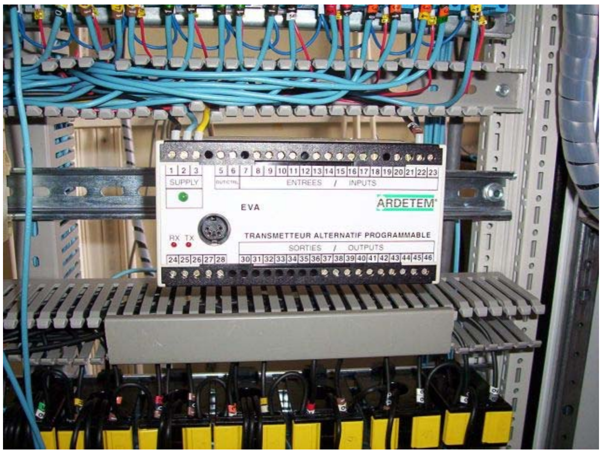


Figure 81:Electrical network analyzer ARDETEM EVA2501

Figure 82: Insolation transducer

Schematic diagrams of loads

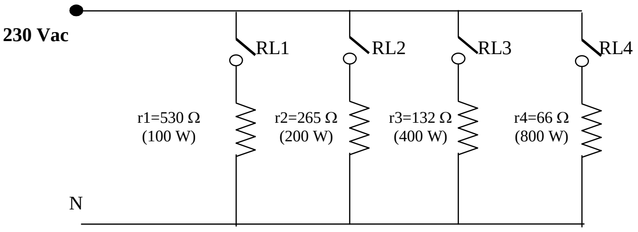


Figure 83: Schematic diagram of resistive loads 0~1500W step 100W

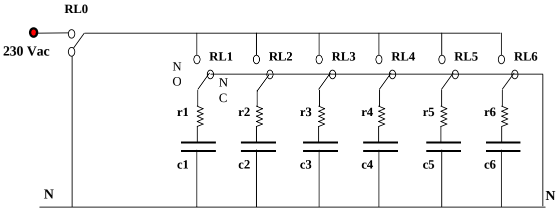


Figure 84: Schematic diagram of the capacitive load 0~ -2094 VAr step –33VAr

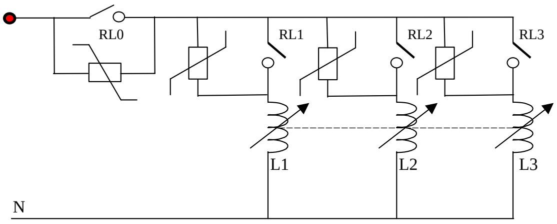
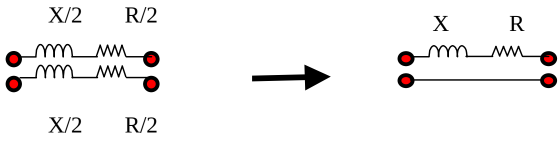


Figure 85: Schematic diagram of the inductive load 0~1380VAr continuously variable

Varistors protect each relay from the excess voltage and electric arc that would be induced by the sudden current fall in the inductances, when opening relays.

Transmission lines

The transmission lines have been modeled by a resistance (R) in series with a reactance (no capacitance has been involved). The values chosen correspond to transmission lines between 100 meters and several kilometers (Table 1.3).



R (Ω)	R/X	X (Ω)	L (mH)
0,1	1,5	0,067	0,212
0,1	3	0,033	0,106
0,1	5	0,020	0,064
0,1	10	0,010	0,032
0,3	1,5	0,200	0,637
0,3	3	0,100	0,318
0,3	5	0,060	0,191
0,3	10	0,030	0,095
1	1,5	0,667	2,122
1	3	0,333	1,061
1	5	0,200	0,637
1	10	0,100	0,318

Table 1.3 Transmission lines values

Security: The WatchDog

The whole system is controlled by the PC. The positions of the relays are memorized by the 34980A. In case of a PC crash (or excessive run time), the system isn't controlled anymore, which may lead to dangerous situations (for the user or the system itself).

An electronic circuit detecting a PC-crash and operating the Emergency Stop has been designed: the WatchDog (Figure 86).

Figure 86: Electronic circuit of the WatchDog

A regularly commutating bit is sent from the PC to the WatchDog via the 34980A (0-1-0-1-0-1-0-1-0…). If the PC crashes, the bit freezes to 0 or 1, which is detected by the WatchDog, thence operating the Emergency Stop.

Software Description

Introduction

Supervision of the system is performed entirely by the PC. A software has been developed for this purpose. One must differentiate the following task levels:

- **visualization and monitoring of the system,**
- **load/source management (for demand/production curves simulation and control),**
- **decision making (corresponding to a Microgrid Central Controller, communicating with source and possibly loads),**
- **results storage (experiments database for further analysis).**

The software has been developed in AGILENT VEE 7 and MATLAB. AGILENT VEE is a complete graphical programming language facilitating communication with the AGILENT 34980A unit and featuring graphical user interface programming (Figure 87). VEE performs visualization (measures & system state) and monitoring of the system, i.e. is the interface with the user.

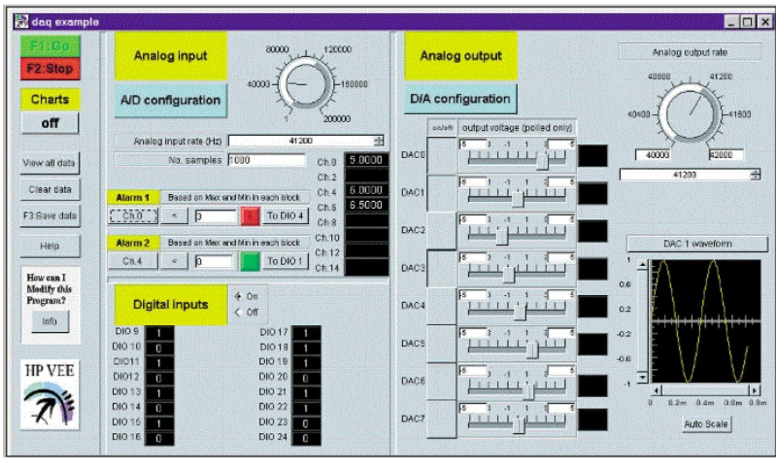


Figure 87: Example of a VEE graphical interface

MATLAB is the supervisor, executing orders and deciding orders to be executed (decision maker). The decision making process is to be implemented in MATLAB by the user, depending, among other things, on measurements.

Software architecture

Here is the diagram of the separate levels in the software (Figure 88):

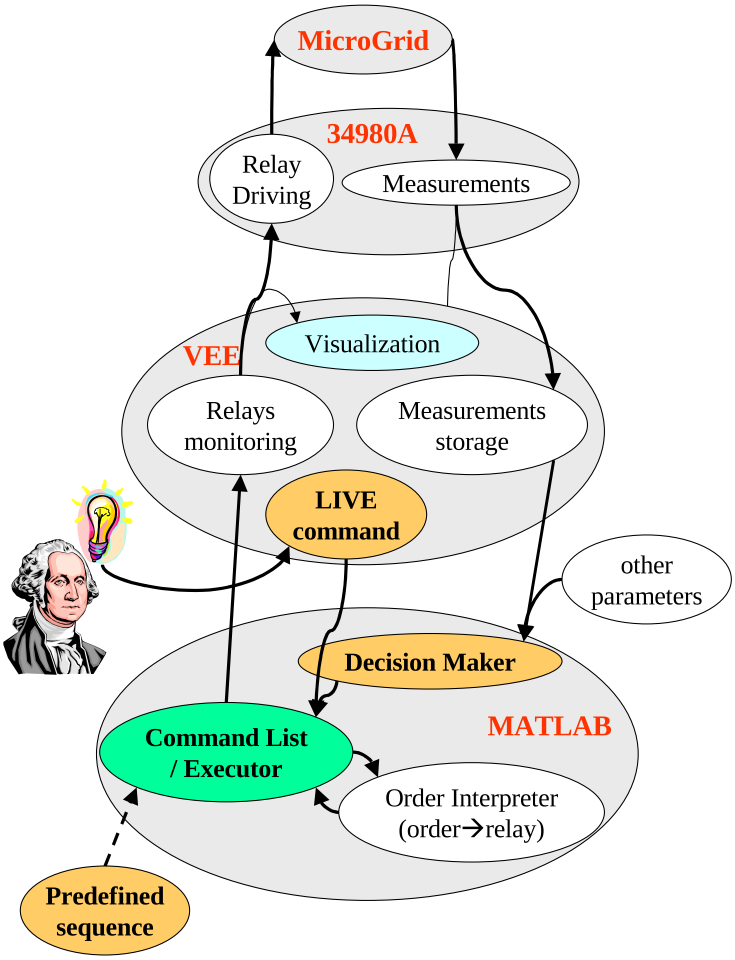


Figure 88: Software architecture

Order interpreter

The **order interpreter** is capable of interpreting human-style orders in terms of relays to open or close. JAVA classes (instantiated in MATLAB) have been defined to create objects corresponding to the microgrid's components (capacitive load, 0~1500W resistive load…) and linking them to corresponding relays. Methods executed on the instantiated MATLAB objects fictitiously update relay positions, and communicates to VEE's relay monitoring the new positions.

A property can be invoked or a method can be executed on an object by using the following syntaxes:
object.property *object.methodname (parameters)*

An order for the system is thence defined as a MATLAB-understandable command **object.methodname (parameters).**

example: CHARGE_RESISTIVE1.setValue(1500) "closes" all the relays of the resistive load R1, setting consumed power to 1500W.

Command List / Executor

A **command list**, containing all the commands sorted by timestamps, is managed by MATLAB. Regularly, MATLAB executes the “past commands” (commands with past timestamp), requesting order interpretation to the order interpreter and sending it to VEE.

Different types of commands: live command, predefined sequence and decision maker module

Users can interact in 3 different ways with the microgrid’s software: by generating a “LIVE” command, by programming a sequence of commands prior to experiment, and by programming the decision maker module.

A command is defined as an order associated to its execution timestamp (yyyy/mm/dd hh:mm:ss format).
COMMAND = TIMESTAMP OF EXECUTION & ORDER

- **LIVE command:** Users can generate a command during execution by pressing buttons on the touch screen, generating an order, and choosing a time of execution (Figure 89).

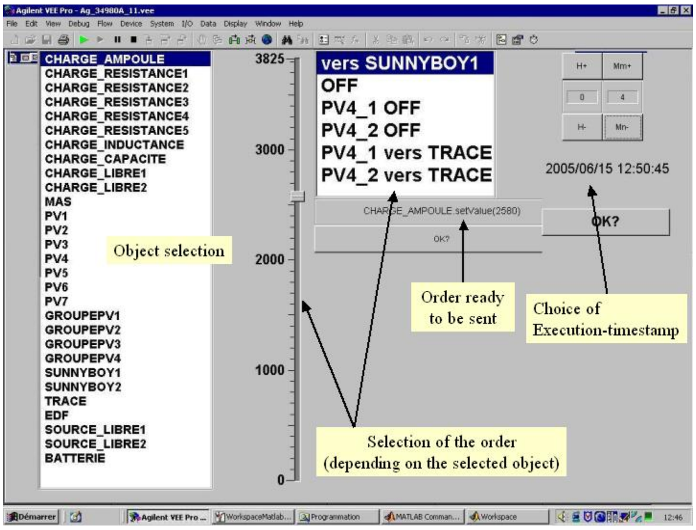


Figure 89: Screenshot of the VEE GUI for the “Live” command construction

- **Programmed command:** It is possible for the user to define in a “**sequence file**” prior to experiment, commands to be executed, the microgrid is then executing a predefined scenario (Table1.4).

INCREMENTAL TIME(S)	EXECUTION TIMESTAMP	ORDER
00:00:20	2005/06/21 10:56:57	CHARGE_INDUCTANCE.globalConnection
00:00:21	2005/06/21 10:56:58	CHARGE_INDUCTANCE.numberConnect(1)
00:00:22	2005/06/21 10:56:59	CHARGE_INDUCTANCE.numberConnect(2)
00:00:23	2005/06/21 10:57:00	CHARGE_INDUCTANCE.numberConnect(3)
00:00:24	2005/06/21 10:57:01	CHARGE_LIBRE1.connect
00:00:25	2005/06/21 10:57:02	CHARGE_LIBRE2.connect
00:00:34	2005/06/21 10:57:11	CHARGE_AMPOULE.setValue(0)
00:00:35	2005/06/21 10:57:12	CHARGE_AMPOULE.setValue(15)
00:00:36	2005/06/21 10:57:13	CHARGE_AMPOULE.setValue(30)
00:00:37	2005/06/21 10:57:14	CHARGE_AMPOULE.setValue(60)
00:00:44	2005/06/21 10:57:21	CHARGE_CAPACITE.globalConnection
00:00:45	2005/06/21 10:57:22	CHARGE_CAPACITE.setValue(0)
00:00:46	2005/06/21 10:57:23	CHARGE_CAPACITE.setValue(2)
00:00:47	2005/06/21 10:57:24	CHARGE_CAPACITE.setValue(4)
00:01:23	2005/06/21 10:58:00	PV1.connect2Trace
00:01:24	2005/06/21 10:58:01	PV2.connect2Trace
00:01:30	2005/06/21 10:58:07	GROUPEPV1.connect2Sma
00:01:31	2005/06/21 10:58:08	GROUPEPV1.connect2TracePV4_1
00:01:32	2005/06/21 10:58:09	GROUPEPV1.connect2TracePV4_2

Table1.4: Example of a "Sequence file"

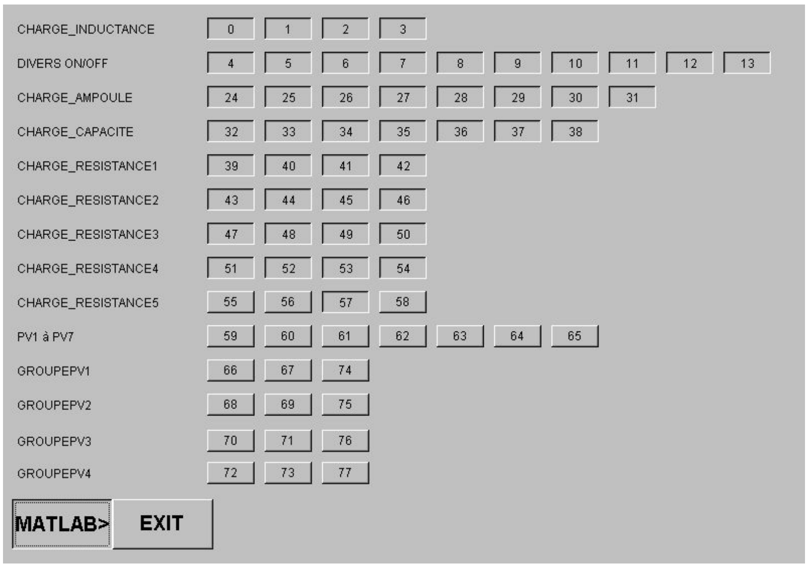
The execution timestamps can be defined either explicitly in 'Execution timestamp' column or relatively to beginning of experiment by filling 'incremental time' column.

- **Automatic command (decision maker module):** Commands are automatically generated during execution by the user-programmable decision maker module, depending on parameters to be defined by the developer, among other things:
  - Time,
  - electrical measures: voltages, currents, powers…,
  - meteorological measures: insolation & temperature,
  - position of the Trace relays…

This module allows to implement different energy management strategies, microgrid central control…

Relay monitoring

Users can check proper execution of their commands in the 'relay monitoring' interface (Figure 90).



CHARGE_INDUCTANCE	0	1	2	3						
DIVERS ON/OFF	4	5	6	7	8	9	10	11	12	13
CHARGE_AMPOULE	24	25	26	27	28	29	30	31		
CHARGE_CAPACITE	32	33	34	35	36	37	38			
CHARGE_RESISTANCE1	39	40	41	42						
CHARGE_RESISTANCE2	43	44	45	46						
CHARGE_RESISTANCE3	47	48	49	50						
CHARGE_RESISTANCE4	51	52	53	54						
CHARGE_RESISTANCE5	55	56	57	58						
PV1 à PV7	59	60	61	62	63	64	65			
GROUPEPV1	66	67	74							
GROUPEPV2	68	69	75							
GROUPEPV3	70	71	76							
GROUPEPV4	72	73	77							

Figure 90: Screenshot of the GUI for relay monitoring

By pressing the MATLAB button, users can deactivate MATLAB supervision and control each relay manually.

Software outputs – Results storage in a database

In addition to controlling the system, the software outputs and stores the more information in a database, allowing users to get information and analyze any experiment made previously, whatever the theme was for the experiment.

Among the software outputs are:

- a "**measure file**" containing all the measures realized, indexed by their timestamp:
- an "**executed file**" containing all the executed commands (orders + timestamp of demanded execution + timestamp of effective execution). This allows to analyze global behavior of the microgrid, considering measurements and a particular decision maker module.

Case study

The following case study is proposed as an initial benchmark for assessing decision maker modules and central control strategies of the microgrid. The microgrid considered is described below (Figure 91).

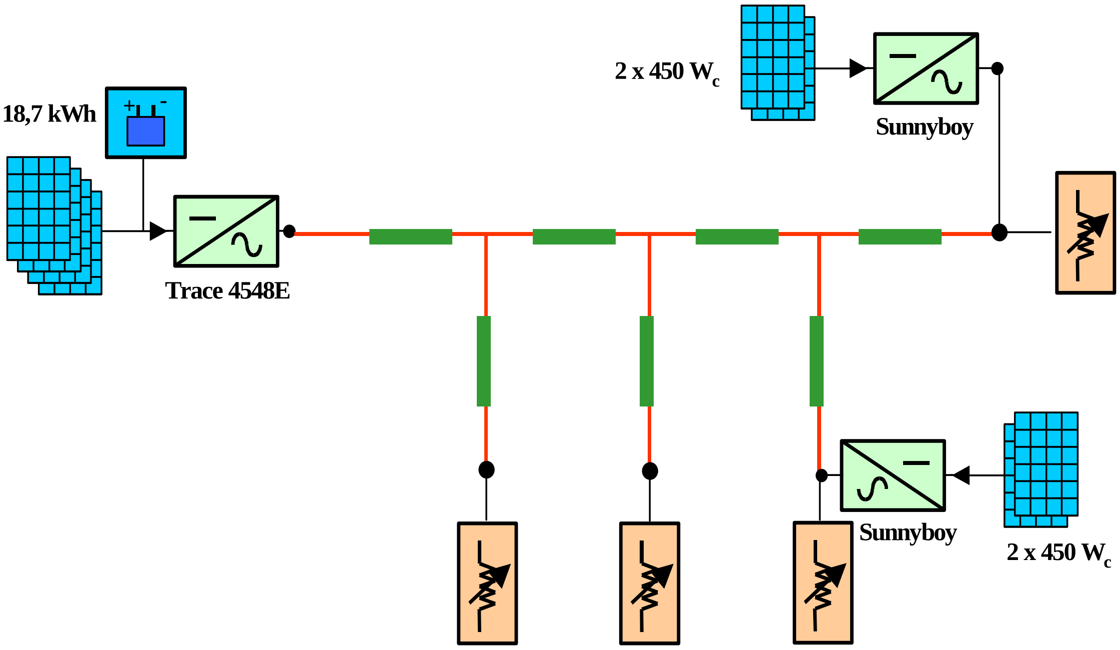


Figure 91: PV/Battery hybrid microgrid

It is assumed that communication between central controller and different components is possible.

Different priority levels are defined for each sub load of the resistive loads represented above.

- non-priority sub loads (NP): they can be disconnected in case of an energy/power supply lack,
- priority sub loads (P): they must be protected from disconnection as long as possible,
- hot water heating (HWH): must be operated for each sub load 1 hour every day at a fixed power

Objectives: Imagine & implement & test energy management strategies to get the best microgrid operation, considering different criteria.