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Table des matières

Nomenclatures des acronymes et conventions

$\widehat{x}$	Grandeur x mesurée
$\widetilde{x}$	Grandeur x estimée
x_per	Grandeur x qui représente des pertes
x_reg	Grandeur x de réglage
x_ref	Grandeur x de référence

ACE	Automate de Commande Eloignée
ACL	Agent Communication Language
ACMM	Automate de Contrôle des Modes de Marche
ACR	Automate de Commande Rapprochée
AG	Active Generator
AGC	Automatic Generation Control
BCC	Bloc de Contrôle des Commutations
BG	Bond Graph
BT	Basse Tension
CC	Chambre de Combustion
CH	Charges (Loads)
COG	Causal Ordering Graph
DER	Distributed Energy Resources
DG	Decentralized Generator
DNC	Distribution Network Controller
DSC	Dispatching System Controller
EMR	Energetic Macroscopic Representation
GIC	Graphe Informationnel Causal
GM	Grid connected Mode
GMT	Gas Micro Turbine
HIL	Hardware-In-the-Loop
HTA	Haute Tension A
IM	Island Mode
IP Controller	Integral-Proportional Controller
LC	Local Controller
MAS	Multi-Agent System
MCC	Microgrid Central Controller
MMN	Modélisation Multi-Niveaux
MPPT	Maximum Power Point Tracker
MTG	Micro Turbine à Gaz
PCC	Point of Common Connection
PFD	Power Flow Diagram
PID Controller	Proportional-Integral-Derivative Controller
POG	Power-Oriented Graphs
PV	PhotoVoltaïque
REBG	Renewable Energy Based Generators
REM	Représentation Energétique Macroscopique
RMN	Représentation Multi-Niveaux
RMS	Root Mean Square
SC	SuperCapacitor
SCH	Structuration de la Commande Hiérarchique
SI Units	International System of Units
SMC	Structure Maximale de la Commande
SMES	Stockage d'Energie Magnétique Supraconductrice
STC	Standard Test Conditions

Introduction générale

Evolution des réseaux électriques

L'architecture des réseaux électriques ainsi que leur gestion sont conçues et adaptées pour alimenter de manière optimale des consommateurs selon les différents modes de production et de consommation. Initialement pensés pour alimenter des consommateurs à partir de centrales de production à base de charbon et de gaz, les réseaux ont évolué de manière majeure dans les années 70 afin de permettre l'intégration de centrales de production de très forte puissance à base d'énergie nucléaire. L'architecture du réseau électrique que nous avons ainsi hérité a été initialement organisée pour alimenter des consommateurs à partir de puissantes centrales de production avec un réseau dédié de transport dont la supervision est centralisée. L'arrivée de nombreuses unités de production de faible puissance (unités de cogénération, générateurs à base d'énergie renouvelable) non interfacées avec un poste de supervision conduira indéniablement dans un premier temps à de profondes mutations sur la gestion du système électrique actuel. Une évolution vers de nouvelles architectures bien adaptées à ces nouveaux modes de production dispersée sera à imaginer pour les temps futurs.

Description des micro réseaux

Un exemple prometteur d'évolution d'architecture de réseau consiste à regrouper les différents producteurs et consommateurs autour d'un réseau moyenne tension pouvant fonctionner en îlotage par rapport au reste du réseau. Ce système est donc composé d'au moins une unité de production décentralisée conventionnelle et éventuellement d'une unité de stockage, le tout étant connecté à un réseau de distribution externe qui permet l'appoint ou l'évacuation d'énergie. Un tel ensemble doit permettre aux clients d'accéder à la qualité, la fiabilité et de satisfaire ses besoins en puissance et constitue en lui-même un réseau insulaire. Sur ce dernier sont connectés des clients qui peuvent avoir le choix d'approvisionnement auprès des divers producteurs décentralisés. Sur un micro réseau (constituant en fait une grappe), l'existence et le fonctionnement d'un marché structuré de vente et d'achat d'électricité se trouve facilité du point de vue technologique. Les excédents de production peuvent être, soit partiellement stockés, soit revendus sur le réseau centralisé ou à une autre grappe via le réseau centralisé, d'où la terminologie 'réseau en grappes'. Du point de vue de la gestion centralisée, l'architecture globale a l'avantage d'être reconfigurable. Toute grappe à l'origine d'une instabilité sur le réseau centralisé peut être isolée. La faisabilité d'une telle organisation de la distribution passe par une gestion intégrée et optimisée de l'énergie qu'il reste à imaginer.

Intérêt des micro réseaux

Les micro réseaux présentent deux caractéristiques intrinsèques essentielles qui en font un intérêt majeur pour le développement des réseaux électriques du futur :

- la proximité entre une production locale d'électricité et les consommateurs conduit à une minimisation immédiate des pertes liées au transport de l'énergie consommée en son sein,
- la disponibilité d'un générateur et son exploitation, toujours en local, apporte une fiabilité accrue de la fourniture vis-à-vis des aléas d'incident survenant dans les grands réseaux et la possibilité de fournir une énergie d'une haute qualité.

Les énergies renouvelables

La disparition prévue des ressources fossiles, associée à une volonté de réduction du taux de CO_2, conduit naturellement à introduire une diversification de la production électrique reposant sur des générateurs à base d'énergie renouvelable, au côté des groupes électrogènes diesel jusqu'à présent uniquement utilisés dans les micro réseaux. Comparés aux unités de production centralisée (tranche nucléaire, …), les générateurs à base d'énergie renouvelable sont de très petites puissances en raison du dimensionnement du système de conversion primaire (surface des panneaux photovoltaïque (PV), longueur des pales, …). Par contre, ce dimensionnement favorise les installations sur un réseau de distribution chez les particuliers et donc en très grand nombre. La croissance de ces filières renouvelables devrait rester très soutenue et ainsi continuer d'augmenter leur part dans la production d'électricité mondiale. En premier lieu, ces technologies ont fait énormément de progrès, que ce soit sur le plan de la fiabilité, ou sur le plan de leur capacité à réduire leurs coûts de production. Ces progrès ont attiré de nouveaux investisseurs intéressés par les perspectives de développement. Ceux-ci ont permis d'augmenter la taille des projets d'énergies renouvelables et donc d'accroître très rapidement le productible de ces filières. En second lieu, les questions globales d'environnement, notamment le risque de changement climatique, ont renforcé la volonté politique de nombreux pays industrialisés à soutenir le développement des énergies non polluantes ou faiblement émissives. Cette volonté s'est traduite par des objectifs ambitieux en termes d'énergies renouvelables et la mise en place d'instruments réglementaires spécifiques pour les atteindre (prix garanti, certificats verts, quotas, fiscalité favorable, etc.) avec comme but à terme de rendre autonomes les différentes filières.

Identification de la problématique

La difficulté majeure associée au développement massif des sources dispersées et à base d'énergie renouvelable est que leur production est difficilement prévisible et très fluctuante. Leur intégration dans le système électrique pose donc un certain nombre de problèmes, par exemple :

- La production d'électricité d'origine « renouvelable » est difficilement prévisible ou très fluctuante (éolien, solaire) ;
- La production d'électricité peut être un processus secondaire, comme c'est le cas dans les unités de production combinée de chaleur et d'électricité ;
- Il en résulte souvent une absence de participation aux services système, parmi lesquels le réglage de la fréquence, via les réglages primaire et secondaire (fréquence-puissance) ou encore au réglage de la tension et de la compensation de l'énergie réactive.

Le fait de ne pas participer aux services système amène ce type de source à se comporter comme des **générateurs passifs** du point de vue de la gestion du réseau électrique. Le taux de pénétration de la production décentralisée doit alors être limité afin de pouvoir garantir la stabilité du réseau dans des conditions acceptables.

Solutions exploratoires et thématiques de recherche à développer

La participation aux services système deviendra techniquement indispensable pour permettre le développement significatif des sources aléatoires (éolien, photovoltaïque). Plusieurs pistes de recherche complémentaires contribueront à lever ce verrou grâce aux **convertisseurs électroniques de puissance** et à l'utilisation de **moyens de stockage** dans le réseau.

Les convertisseurs électroniques de puissance permettent de connecter sur le réseau des dispositifs de production de technologies variées et d'introduire des possibilités de réglage qui amènent :

- à imaginer des structures adaptées pour les unités de production décentralisée conduisant à de meilleurs rendements,

- à influer sur les flux de puissance et la répartition énergétique des différentes sources présentes dans un réseau électrique.

Cependant, leur exploitation nécessite de concevoir de nouvelles lois de commande, d’intégrer des services « systèmes » et de revoir les stratégies locales de supervision pour ces unités de productions auxquelles les convertisseurs électroniques de puissance sont raccordés. L’ensemble de ces travaux à mener vise à rendre compatible les unités de production à base d’énergie renouvelable avec le système de gestion du micro réseau électrique de manière à lever les limitations actuelles à leur expansion.

Un deuxième ensemble de solutions vise à développer une gestion intégrée et optimisée de l’énergie au sein du micro réseau électrique qui devient ainsi un système multisource comportant une multiplicité de points de réglage. Un système multi source, avec une gestion intégrée et optimisée de l’énergie, est constituée de différentes catégories de générateurs (par exemple : éolien, photovoltaïque, micro turbine hydraulique, micro turbine à gaz, pile à combustible, etc.) pouvant être éventuellement associés à différents systèmes de stockage (par exemple : batterie, volant d’inertie, stockage électromagnétique ou stockage d’énergie magnétique supraconductrice (SMES), super condensateur, pompage hydraulique, compression d’air, etc.). Les générateurs et systèmes de stockage peuvent être localisés en différents points du réseau, mais sont gérés par un opérateur industriel unique. Dans ce mémoire, nous étudions un micro réseau reposant sur l’utilisation d’une turbine à gaz, d’une centrale PV et d’une unité de stockage à base de supercondensateurs. Toutes ces sources sont couplées au micro réseau par des convertisseurs électroniques de puissance et sont interconnectées au gestionnaire central du micro-réseau (Microgrid System Operator) (Figure 1).

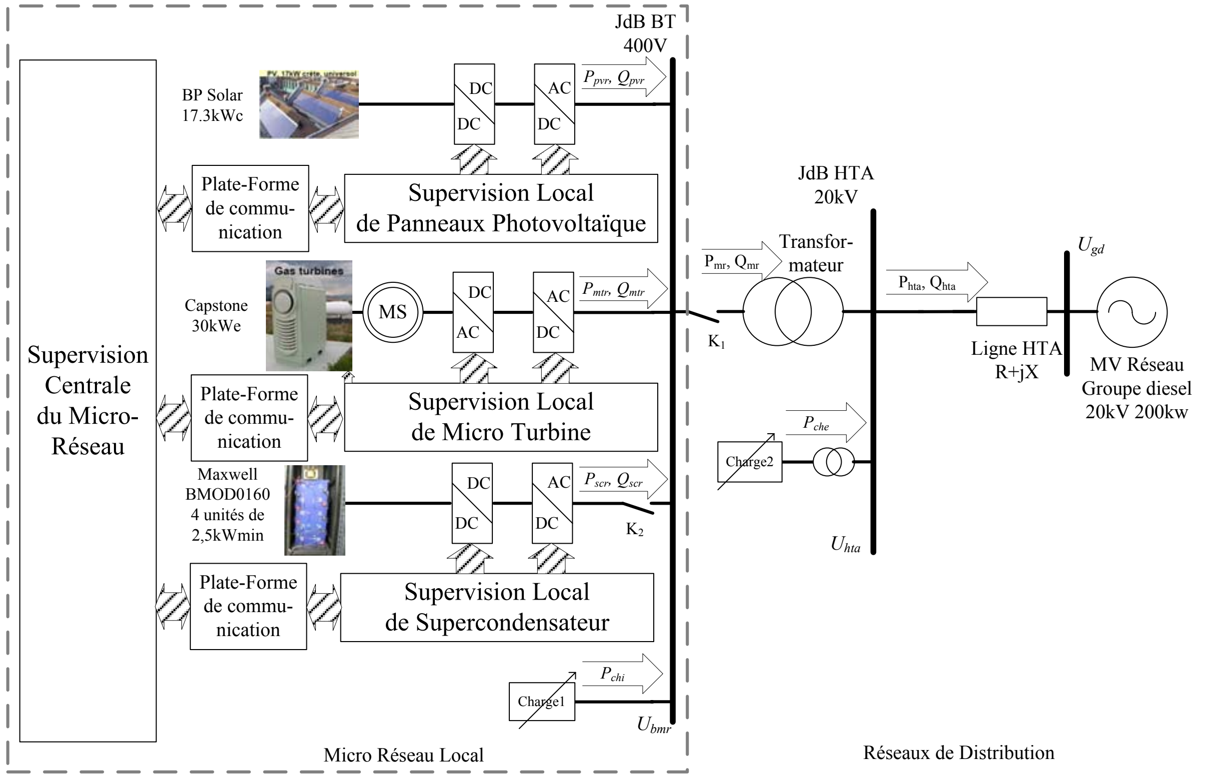


Figure 1. Schéma global du micro réseau étudié

Méthode suivie et organisation du mémoire

Tout d'abord, il s'agit de développer le concept de générateur actif c'est-à-dire d'implanter toutes les fonctions nécessaires pour faire participer ces petits générateurs à la gestion du micro réseau. La première partie de cette thèse présente les travaux ayant permis d'adapter les dispositifs de commande aux nouvelles formes de sources à base d'énergie renouvelable en prenant en compte les conditions de fonctionnement irrégulier et l'interfaçage au réseau via de l'électronique de puissance. Il s'agit de :

- Modifier les lois de réglage sur des générateurs existants et valider l'implantation de techniques nouvelles permettant la fourniture de services système (par exemple en vue de participer au réglage de tension ou de fréquence),
- Valider les modèles et stratégies de commande du stockage disponibles,
- Valider des stratégies de supervision innovantes, capable de répondre aux sollicitations nécessaires à la gestion du réseau et les interfaces correspondantes avec le système.

Dans cette logique, la première partie de ce mémoire est consacrée à la formalisation d'une méthode permettant la conception systématique des supervisions locales et des dispositifs de commande des unités de production et de stockage.

La seconde partie de cette thèse est consacrée à la gestion proprement dite de l'ensemble de ces moyens de production et de stockage en vue d'optimiser les services fournis aux micro-réseaux. L'objectif est d'en améliorer la fiabilité tout en augmentant l'efficacité énergétique. Les sources renouvelables plus ou moins aléatoires (éolien, photovoltaïque, hydraulique) sont au cœur des problèmes avec comme objectif de proposer des solutions contribuant à augmenter leur taux de pénétration. L'enjeu majeur est le développement d'une approche méthodologique pour la conception de la supervision énergétique du micro réseau. Cette supervision doit déterminer les grandeurs de référence permettant de satisfaire en temps réel des objectifs déterminés, et ce malgré un caractère fluctuant et mal déterminé de l'environnement (source primaire, état du réseau, charges,…). La production des sources et la sollicitation des éléments de stockage doivent être modulées en fonction des besoins du réseau.

Partie I

Méthodologie de conception des supervisions locales et dispositifs de commande des unités de production et de stockage

Présentation des objectifs et méthodologie

La première partie de la thèse concerne la conception des supervisions locales et des dispositifs de commande des unités de production et de stockage raccordées à un micro réseau.

Les dispositifs permettant de convertir les sources primaires d'origine renouvelables ne peuvent pas être directement connectées à un réseau triphasé alternatif de fréquence constante à 50Hz. Par exemple, les panneaux photovoltaïques sont des sources de courant continu [RAU-80] [ZUB-00] [MAX-04] [PAN-04], les micro turbines à gaz associées à une machine synchrone tournent à une grande vitesse et fournissent des courants de hautes fréquences [LAS-01] [NIK-05]. Des convertisseurs électroniques de puissance sont donc nécessaires pour les adapter au réseau triphasé [GAZ-06] [KAT-08]. Dans ce contexte, un dispositif de commande sophistiqué est obligatoire pour piloter les convertisseurs statiques et superviser le fonctionnement des différents éléments réalisant les conversions énergétiques jusqu'au réseau électrique.

Une supervision locale des différents éléments constitutifs du générateur est nécessaire.

Nous avons choisi une supervision locale communicante basée sur des puissances de référence, car pour un micro-réseau, toutes les unités de stockage sont proches. Cette proximité de la production, de la consommation et du stockage permet une installation facile d'un bus de communication. Des supervisions locales peuvent donc être conçues en recevant les consignes données par une supervision centrale par l'intermédiaire du bus de communication. Leur exploitation optimale est donc rendue possible en prenant en compte des informations sur leurs fonctionnements.

Un formalisme est nécessaire pour guider et rendre systématique la modélisation et la conception de la commande de chaque générateur. Actuellement parmi les formalismes existants, il n'y pas de formalisme qui permet de systématiser le calcul des puissances et le transit de la puissance au sein des éléments de l'une unité de production ou de stockage. Ce formalisme a pour objectif la conception d'un système de commande adéquat vis-à-vis de la supervision locale [LIP-06A] [LIP-08A].

Dans ce contexte, nous proposons un formalisme basé sur une Représentation Multi Niveaux de la modélisation et de la structure de la commande selon une hiérarchie ordonnée également en plusieurs niveaux. Ce formalisme permet d'automatiser la modélisation du transit de la puissance au sein du générateur et surtout permet de formaliser la conception de la supervision locale.

La première partie de cette thèse est donc organisée de la manière suivante :

Le chapitre I analyse les avantages et les limites des formalismes existants pour la conception de la supervision locale. Trois formalismes sont souvent utilisés, le Bond –Graph, le Graphe Information Causal (GIC) et la Représentation Energétique Macroscopique (REM), sont analysés à travers leur utilisation pour le contrôle de deux unités types au sein d'un micro réseau : un système de production basé sur la micro turbine à gaz qui est une production programmable ou encore contrôlable par le gestionnaire du micro réseau et un système photovoltaïques qui est une production non-programmable encore qualifiée de fatale. Par ce moyen, les limites communes aux formalismes sont mises en évidence.

Le chapitre II présente notre proposition, la Représentation Multi-Niveaux (RMN), pour résoudre ces limites. Ses principes de modélisation et de commande sont introduits dans ce chapitre pour analyser des éléments typiques au sein d'une unité de production ou de stockage.

Le chapitre III présente l'application de la RMN à une micro turbine à gaz. L'analyse sur ce système nous permet d'illustrer les étapes qui nous conduisent à la conception d'une supervision locale de manière synthétique et systématique par la RMN.

Le chapitre IV présente l'application de la RMN à un système photovoltaïque et un système de stockage basé sur des super condensateurs. Un premier intérêt de ce chapitre est de montrer que la RMN est un formalisme universel pour la conception d'une supervision locale d'unités diverses. Ensuite, ce chapitre met en évidence l'intérêt de la RMN par le fait que deux systèmes de structures similaires peuvent conduire à deux supervisions locales très différentes selon les capacités du système étudié et les objectifs du gestionnaire du micro réseau.

Part II.

Supervision of a micro grid by a central controller

The scope of the second part of this research report is the development of new strategies and new implementation of management techniques for microgrids in presence of renewable energy based generators. First, let us recall fundamental principles of grid management systems and classical practices in order to better highlight studied problems in this second part.

Isochronous Speed Control Mode

Isolated power systems and industrial microgrids are relatively small power systems. They are usually powered by an AC single generator, which is driven by a gas turbine or a diesel engine generator. The frequency of a synchronous AC generator is directly proportional to the speed of the rotating electrical field. Hence the power management relies on a simple Isochronous Speed Mode Control. The Isochronous Speed Control Mode uses the physical principle of grid connected synchronous machine stator, which induces the exact synchronization of the machine speed with the grid frequency. A controller operating in the Isochronous Speed Control Mode maintains the turbine at a constant speed. Hence the energy being admitted to the prime mover is regulated in response to changes in load, which would tend to cause changes in the speed. Any increase in load would tend to cause the speed to decrease, but energy is quickly admitted to the prime mover to maintain the speed at the set point. Any decrease in load would tend to cause the speed to increase, but energy is quickly reduced to the prime mover to maintain the speed at the set point.

Power management with many Decentralized Generators (DG)

To increase the total generated power, multiple machines must be connected in parallel but it is then impossible to run them at exactly the same speed. If all prime movers operate in Isochronous Speed Mode, they will usually "fight" to control the frequency and wild oscillations of the grid frequency result. The machine, which runs faster may absorb all the loads while the slightly slower machine will shed all its load. So when multiple units are being operated in ”parallel”, only one machine can have its governor operating in Isochronous Speed Mode for a stable grid frequency control That has conducted to define other control functions as Droop Speed Control Mode and Fixed Power Control Mode.

Droop Speed Control Mode

A controller operating in the Droop Speed Control Mode controls the turbine speed as a function (the droop characteristic) of turbine load. The Droop Speed Control Mode, in fact, refers to the fact that the energy being admitted to the prime mover of the AC generator is being controlled in response to the difference between a speed (frequency) setpoint and the actual speed (frequency) of the prime mover. To increase the power output of the generator, the controller increases the speed setpoint of the prime mover, but since the speed cannot change (it's fixed by the frequency of the grid to which the generator is connected) the error, or difference, is used to increase the energy being admitted to the prime mover. So, the actual speed is being "allowed" to "droop" below its setpoint.

Current practices for grid management

A grid may include turbines having both Droop and Isochronous Speed controllers. Such a system typically comprises a main generating unit operating in the Isochronous Speed Mode to maintain the output electric power at a constant frequency and one or more booster generating units, which operates in the Droop Speed Control mode. In this arrangement the droop controlled units are adjusted to share the load with the main generating unit so as to assure that the isochronous controller is able to maintain a constant speed. As shown droop control based power management allows different size generators to balance a load between themselves based on their individual abilities. Organization and setting of the various parameters for a correct power sharing is quite difficult and definitely impossible if we want to maximize economic or environmental criteria.

For a practical organization, the implementation is organized into primary and secondary control. The primary control is activated if the load increases. Hence the frequency droops and the Droop Speed control will increase the generator speed to increase the generated power proportionally to the generator droop characteristic (regulation). The secondary control is necessary otherwise the frequency will remain below the normalized value (50Hz in France). It is now up to the operator to increase the generator output more to bring the frequency back to the normalized value. So this isochronous action is required and just does the "correction" for the generator to return frequency back to the normalized value. So the grid management is a combination of droop controller with a time constraint on how fast to make the correction to bring frequency back via an isochronous action.

Remark:

On very large electrical grids, commonly referred to as "infinite" electrical grids, there is no single machine operating in Isochronous Speed Control Mode, which is capable of controlling the grid frequency. All prime movers are being operated in Droop Speed Control mode. But there are so many of them and the electrical grid is so large that no single unit can cause the grid frequency to increase or decrease by more than a few hundredths of a percent as it is loaded or unloaded.

Fixed Power Control Mode in grid connected operation

When running in parallel with the grid, small DG units and in particular renewable energy based generators are not obliged to participate in frequency or voltage regulation until now. Hence a Fixed Power Control Mode is adopted and dispatches a fixed amount of real and reactive power to the system. Moreover for Renewable Energy Based DG the power reference is adapted according to the meteorological conditions in order to generate the maximum power. In consequence frequency or voltage regulation is reported to large AC generators in the grid. This can be the case if our studied microgrid is connected to a distribution network.

Grid connection with power electronic converters

Obviously modern high speed microturbines and major of DG are grid-connected with power electronic converters and so no physical relations exist between the rotor of the machine and the grid frequency. Moreover the large scale development of PV generators as well as technological evolution of storage units (supercapacitors as example) makes appear DG without any electrical rotating machine. The presented power management techniques has to be adapted via additional control functions to make fully compatible “power electronic converter based generators” with existing high power machine based generators.

Specificities in islanded mode

There is a need of control switching between the grid-parallel and islanding operation. In an islanded mode, DG units have to be immediately switched to a « voltage and frequency control » mode since these physical quantities are not controlled. The purpose is to supply the local load demand inside the microgrid whilst regulating the frequency and voltage within permissible limits. When more than one DG units operate into voltage and frequency mode problems arise as all of them try to control these electrical quantities with their own setting. Thus proper coordination between the DG units is clearly required in islanded mode.

Content of this part

In this research work all DG are grid–connected with power electronic converters. In addition a PV generator is a source of power fluctuations, which has to be compensated. Moreover the studied microgrid must have the ability to be connected with a distribution network. In the first part of this report, local controllers of DG units have been enhanced in order to realize the independent and simultaneous control of the active and the reactive power. Hence, the gas micro turbine and the supercapacitor unit are able to exchange a predetermined real and reactive power with the microgrid. These new control capabilities have been developed in order to create new possibilities to manage a microgrid in presence of renewable energy based generators.

In the second part of this report we propose a centralized control, which makes benefit of a communication bus for information exchanges between embedded Local Controllers in DG and a Microgrid Central Controller. The chosen scheme for the microgrid management is a combination of an Isochronous Load Sharing with adapted and dedicated Droop Control Mode for some DG.

As shown the required control of a microgrid is significantly different from those of conventional power systems. The next chapter presents the context of the studied centralized supervision and the proposed organization of the microgrid system. Hence the chapter VI presents the power management scheme for a grid connected mode. The modelling of the distribution network and the microgrid is detailed and more precisely the coupling bus. The chapter VII concerns the microgrid operation in islanded mode. Additional functions to form an autonomous grid are required for the power management and energy management of the microgrid. Experimental tests are presented with the help of a real supercapacitor based distributed storage, which is interfaced with a 15kW amplifier to a real-time simulator.

Chapter V.
Controls and operation aspects of a microgrid

V.1. Introduction

In this chapter, a brief introduction to microgrid supervisions and a succinct presentation of existing research results about microgrids will be presented. Its purpose is to facilitate the understanding of the context of the thesis research work on central supervision of microgrids. The multi-agent system (decentralized control) and the global supervision control (centralized control) will be presented in the following paragraphs. Their advantages and disadvantages will be illustrated in the research framework of our studied microgrid. The details of our proposed central supervision will be presented in the next chapters.

V.2. General principles and functions

The task of microgrid supervision is to manage the power and the energy between sources and loads. Then the real and reactive power must be shared among the DER units. So the microgrid controller must assign real and reactive power references and also other appropriate control signals to the DER units, storage units and controllable loads. In the first part of this report we have enhanced control systems of studied DER in order to be fully compatible with this organization.

Power management system and energy management system are more complex for microgrid applications. The first reason is that it has to manage a large number of small DER units with different capacities and characteristics. A second reason is that most of DER is coupled to the grid with power electronic converters and so may have fast responses. Moreover if conventional generators are also coupled their voltage/angle stability may be affected.

The microgrid supervision will be analyzed through various functions, which are classified in a timing scale (Figure V-1).

The short-term power balancing includes:

- the real time “Balancing and power dispatching” among DER units and storage units according to the storage level capacity and to the specific requirements/limitations of each DER unit, including available power from Renewable Energy Based Generators (REBG),
- the RMS voltage regulation and primary frequency control.

The long-term energy management includes:

- the hourly “RES production forecast” including the time dependency of the prime source, environmental impacts and cost of generation,
- the management of non-sensitive loads that may be disconnected/shed according to the supervision requirement,
- the maintenance intervals,
- the provision of an appropriate level of power reserve capacity according to the electricity market and the load demand forecast.

In a classical vertical integrated electrical system, long term energy management is implemented by the Grid System Operator and the short term power balancing is implemented into generators (with a droop speed controller).

Two types of microgrid central supervisions for distributed energy resources (DER) exist [KAT-08] [PED-08]:

- Control by sensing electrical quantities. This method is achieved by using the knowledge of physical quantities at the Point of Common Connection (PCC) [LAS-02] [KAT-06] and a droop characteristic control;
- Control by signal communication. This method uses a communication bus to exchange information and control signals [DIM-05] [BAR-05] [GAZ-06] [DEG-06] [DIM-07].

The details of these two types of control are presented in the following paragraph. And discussions about the choice for our studied microgrid are carried out.

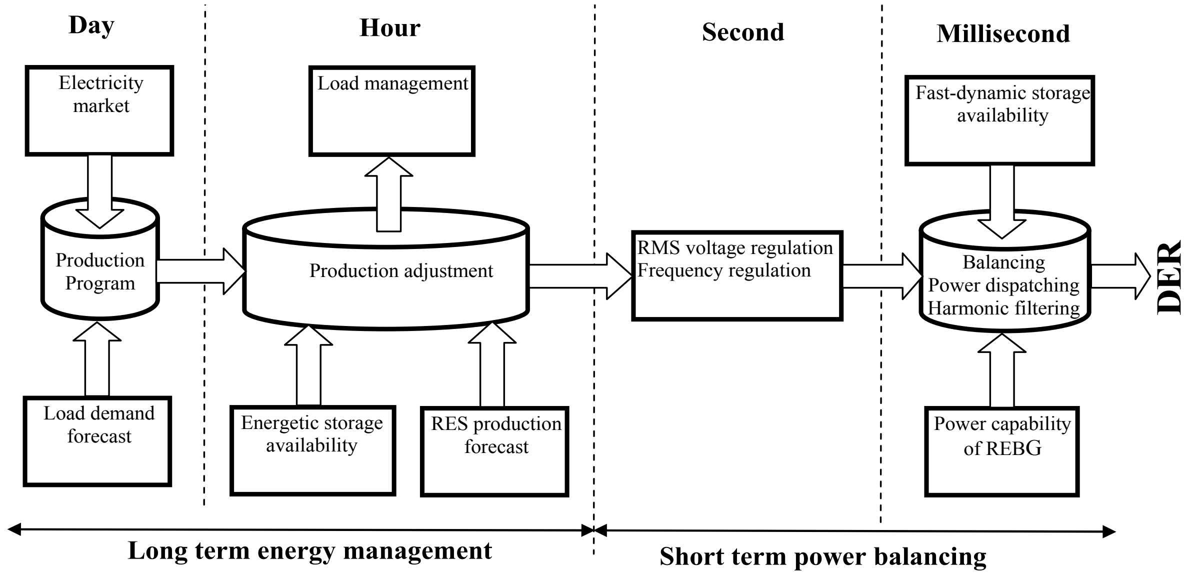


Figure V-1. Timing classification of control functions in the context of microgrid

V.3. Microgrid control by sensing electrical quantities

In Europe, electrical networks have been developed after the Second World War. At this time, communication infrastructures were limited. Coordination of all generators has been implemented through the measurement of two grid physical dynamic quantities: the frequency and the RMS value of the microgrid voltage [LAS-02] [KAT-06]. With the information, a droop characteristic control performs the coordination of Local Controllers (of generators) with a frequency-real power droop characteristic and/or voltage-reactive power droop characteristic. For example, when the frequency decreases the characteristic modifies the power reference in order to increase the generated real power. A local supervision of internal power and energy flows is therefore required as previously detailed in part 1 in the « Power dispatching control scheme » of the gas microturbine (chapter 3, Figure III-15, Figure III-17) or the supercapacitor unit (chapter 4, Figure IV-20, Figure IV-22). A droop controller can be easily used in local controllers to set real and reactive power references for a « Power dispatching control scheme » as shown on Figure V-2 for the supercapacitor units.

The main advantage of this method is its simple hardware implementations, since the development of central supervision devices is unnecessary. Moreover this local implementation enables a very fast response and then a good adequacy for frequency control and RMS voltage regulation (Figure V-1). This organization works in an autonomous way and sometimes called “non interactive” since is not coordinated with a higher control center. The main disadvantage is the fact that an optimization function of the microgrid can not be designed with accuracy, since no sufficient information is known from operating points of other generators.

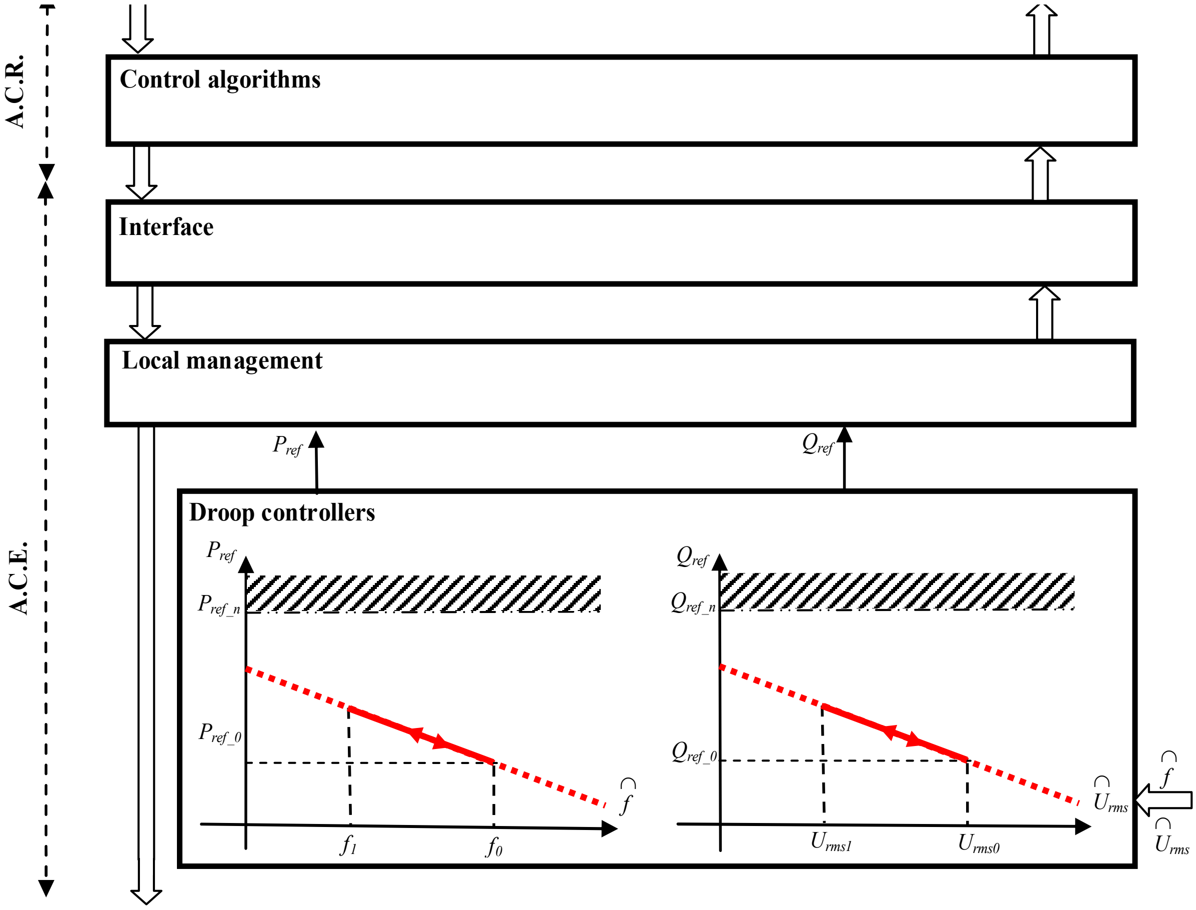


Figure V-2. Droop controllers for the « Power dispatching control scheme »

V.4. Microgrid control by signal communication

V.4.1. Introduction

Control by signal communication enables information exchange and includes three categories of controllers as shown in Figure V-3 [KAT-08]:
- Distribution Network Controller (DNC);
- Microgrid Central Controller (MCC);
- Local Controllers (LCs), which are associated with each Active Generator (AG) or loads.

An active generator is considered as a generator whose participates to the management of the grid. This type of system organization implies either a centralized control achieved by a global supervision function [DEG-06], either a decentralized control, which uses the results of negotiations between agents of every LC functions (multi-agent systems) [DIM-05] [DIM-07].

The DNC is intended for an area in which more than one microgrid exists. It does not belong to the microgrid but is the delegate of the distribution network. The main interface between the DNC and the microgrid is the MCC. The MCC assumes different roles ranging from the maximization of the microgrid value to the coordination of LCs.

The LC controls the DER units and the controllable loads.

In a centralized operation, each LC receives set points from the corresponding MCC. In the first part of this report we have designed several LCs for various DER in order to implement the received set points and in order to send to MCC information about their operating point.

In a decentralized operation, each LC makes decisions locally.

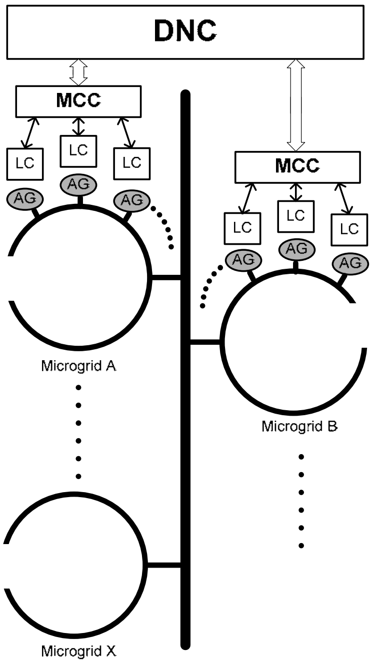


Figure V-3. A microgrid supervisory control architecture

V.4.2. Decentralized control : Multi-Agent System (MAS)

A main feature of the MAS is that the software within each agent can embed local intelligence. Each agent uses its intelligence to determine future actions and independently influences its environment [REH-03] [BAR-05] [DIM-07] (Figure V-4).

An intelligent microgrid requires a fairly advanced communication system with capabilities similar to the human speech; for example, the Agent Communication Language (ACL) provides an environment for information and knowledge exchange. The need for a high-level communication environment can be shown by considering the communication needs of two agents within a microgrid. For example, at a given time one may have an instantaneous surplus of 1,500 W and the other may need 500 W. It is neither efficient nor required to provide the exact values, since the situation can change within a short time. The ACL provides the environment to exchange messages of the form “I have currently some watts and do not expect to use them in the next 30 minutes” or “I need a few extra watts in the next 30 minutes.”

The agents exchange not only simple values and on-off signals but also knowledge, commands, beliefs, and procedures to be followed through the ACL. For example, the agent that controls a load can participate in the local micro-grid market by sending a request message to all DER agents stating the amount of required energy. Furthermore, its object-oriented nature and data abstraction enables each agent to handle only the necessary or allowable information and knowledge.

Figure V-4 shows a decentralized microgrid control structure. The higher level (“Agent of DNC”) corresponds to a medium-voltage network (grid level) and its agent is responsible for communication between the microgrid and the DNC and the message exchange regarding the energy market. The medium level is the management level in which the agents of all MCCs coordinate:

- Controllers of DER/load units;

- Market participation;
- Possible collaborations with the adjacent microgrids.

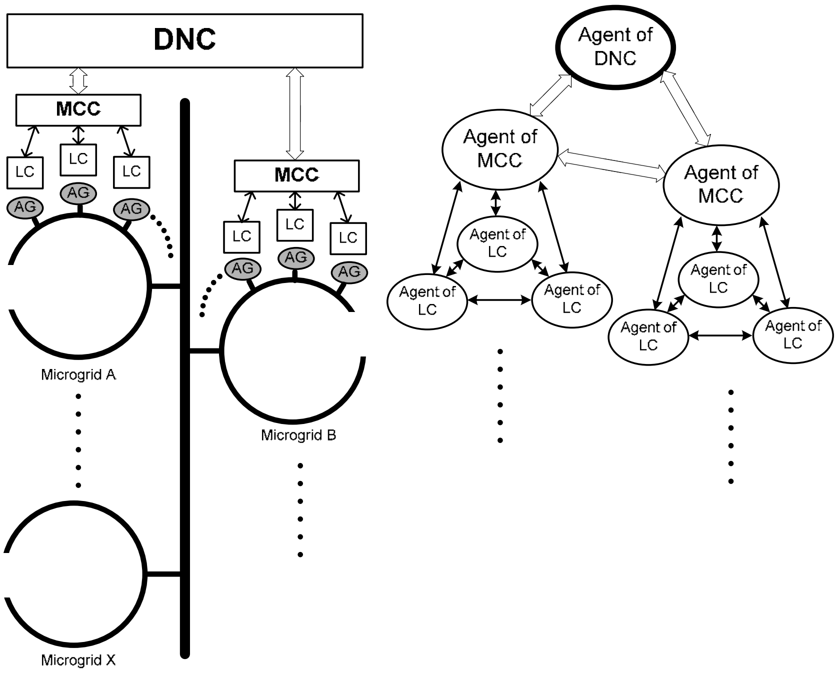


Figure V-4. Schematic diagram of the MAS architecture for a decentralized microgrid control

The bids and the offers result from negotiations among the local agents (“Agent of LC”). Operation of LCs requires an external part and an inner part. The external part provides interface with the microgrid and is identical for all LCs to exchange set points, bids and commands. The inner part is specific to each LC and responsible for translating orders and/or set points and applying them to the corresponding unit. For example, Figure V-5 details inner and external part of the supercapacitor LC.

The main challenge of this method is to develop communication functions such that a new functionality requires minimum changes in the agent-based software. To add a new functionality, all that should be required is to train the agents to deal with a new type of message or a new object. The method is also used to coordinate a large amount of production systems whose task can not be easily clarified. However, in our studied microgrid, each of the three typical production systems has respectively specified task (a dispatchable generator for a long-term power management, a non-dispatchable generator for a MPPT power generation, and a storage system for a short-term power management). The method necessitates also the construction of a complicated communication interface. This is not the case of our application, in which only some simple communication interface devices are available.

Therefore, the centralized microgrid control is chosen for our study.

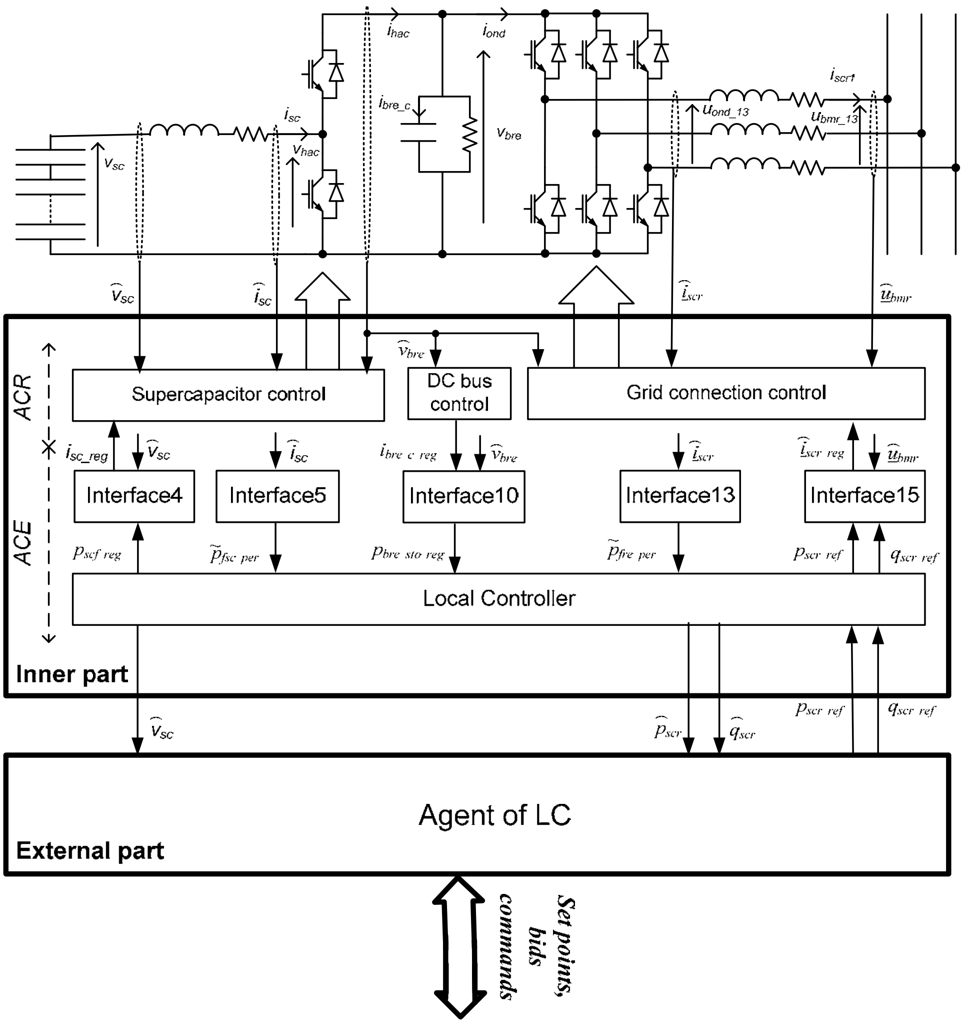


Figure V-5. Supercapacitor LC for a decentralized microgrid control

V.4.3. Centralized Control : Microgrid Global Supervision

With a centralized control method, the MCC takes into account constrains in order to perform an optimization operating. The constraints can be:
- DER and loads operating point;
- Market prices;
- Network security constrains;
- Demand and/or renewable production forecasts.

This optimization is achieved by receiving the information from LCs and by sending the control references to LCs. LCs are simplified to the unique inner part as described in the part 1 of this report. The MCC calculates the control reference and the necessary data for the optimization, such as:
- Power references for DER units;
- Set points for the non-critical loads;
- Market prices for the next optimization period.

Therefore, the LCs can adjust their own operating points by using the reference signals send by the MCC as explained in the first part of this report for each source. The MCC is constructed by considering a formulation of constrains, an implantation of economic optimizations and an interface with LCs (Figure V-6).

The constraints depend on the weather forecasts, which have an impact on the daily load profiles and the energy potential of the intermittent renewable primary sources. The exploitation cost of microgrid generators is present in the constraints and also the environment impacts (by taking into account the generators using fossil energy, the efficiency of different generators…).

On the technical level, the ancillary services for the whole microgrid are quantified and dispatched to the different generators. Moreover, the function mode of every generator is also specified. From available information (the frequency, the AC bus voltage, the storage level, etc.), these algorithms make the necessary decisions for the generators, in order to provide a correct function of the microgrid.

The interface in the MCC enables the real-time generation of the references for each generator according to a selected function mode. It shapes also the information of generators about their availability (set point, storage level, production potential, etc., an example is given at the Annex 7).

Figure V-6 illustrates the information exchange path in a central supervision and indicates that a two-way communication bus between the MCC and each LC is required for control signals and information signals of the generator. The communication can be performed through electric cables, optic cable with photoelectric devices, telephone lines, power line carriers, or a wireless transmission, an intranet or the internet, etc. For our experimental work, electric cables are used to communicate the signals between the central supervision and the LCs. The details will be given in the last chapter.

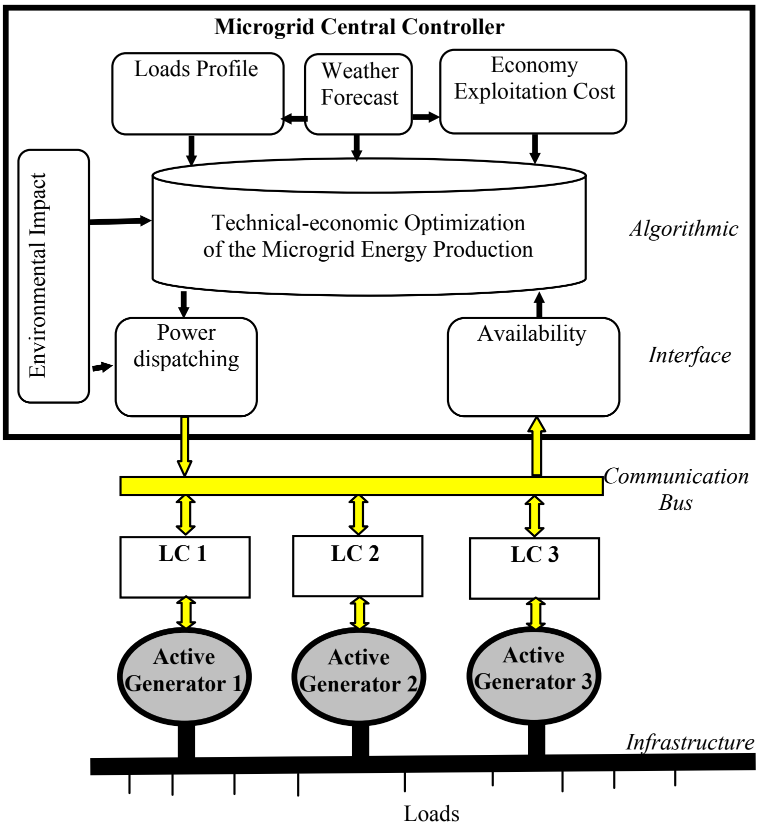


Figure V-6. Architecture of a MCC

The economic considerations and the prevision are not in the scope of this PhD thesis. We will focus on the power dispatching and the ancillary services, which are the basic element to ensure the operation of our studied microgrid. Other considerations can be integrated by modifying our achieved fundamental functions.

The architecture of two MCC will be detailed for two operating modes of the microgrid. In a grid connected mode with a distribution network, the microgrid is considered as an independent electricity producer and a specific interface has to be developed in order to synthesis the necessary information for the MCC (chapter VI). In an islanded mode, additional functions, such as the voltage control, must be added to the MCC (chapter VII).

V.5. System organization of our studied microgrid

Obviously the design of a microgrid supervision depends on the capacity of generators to participate to the microgrid management. In our study we have considered three different types of generators. The availability of electrical energy is ensured by a 28 kW gas microturbine and we are going to use it for long term energy management (Figure V-1). Renewable energy based electrical production is considered by a 17.3kW (peak power) PV generator. The third type of unit is a storage system, which is based on supercapacitors. As there energy density is small we can use it only for short term power balancing (Figure V-1). Moreover supercapacitors have short time response constants and so are able to provide fast the amount of power required to balance the system following disturbances and/or significant load changes. For the microgrid central controller all three micro generators constitute a virtual prime mover.

All generators are grid connected with power electronic converters. Grid-inverter control is thus an important concern for the microgrid operation. Figure V-7 shows for both modes (islanded mode and grid-connected mode) possible local control schemes and the possible organization for the microgrid supervision. In this work we will study just non-greyscale possibilities.

In islanded mode the gas microturbine is chosen as the single master generator in the microgrid system because it is the dominant source of energy generation. Hence an indirect Isochronous Speed Control Mode is implemented by the use of the « Grid-forming control scheme ». The grid-inverter controls the microgrid voltage with pre-defined voltage rms and frequency values. In case of a load increase grid currents (i_{ond}) will be extracted from the DC bus. Hence the machine torque (C_{em}) will be adapted to maintain constant the DC bus voltage. In consequence more fuel will be injected to maintain constant the speed of the microturbine (Figure III-18).

In grid-connected mode the voltage is imposed by the distribution grid. Then the microturbine has to work in a Droop Speed Control Mode. We are going to make benefit of a communication bus in order to share this control function among all generators. So a « Power dispatching control scheme » is used for the gas microturbine in order to supply a given real and reactive power set-point (Figure III-15).

In order to maximise the use of renewable energy, the PV generator is working in “Grid-following control scheme” and all converted power is sent to the microgrid. Moreover in order to facilitate the microgrid management the knowledge of the produced power is available via the communication bus.

To implement the short term power balancing onto the supercapacitor unit a « Power dispatching control scheme » has been used in order to set prescribed real and reactive powers as for the microturbine in grid-connected mode (Figure III-15).

The microgrid central controller measures the microgrid state variables and dispatches orders to micro sources using the communication bus. Local controllers of the microturbine and the supercapacitor unit receive power set points from the microturbine central controller. In the same time they send various informations, as example the sensed power production of the unit. Hence the MCC has to manage the microturbine and the supercapacitor unit in order to control the microgrid. Two cases of study are tackled for the grid-connected mode (chapter 6) and for the islanded mode (chapter 7). For this organization the gas microturbine has to sense electrical quantities and moreover send information signals to the MCC.

Islanded mode

Micro sources	Local control scheme	Organization	
Renewable Energy Based Generators	Grid-following		
Gas Microturbine	Grid-forming	by sensing electrical quantities	
Supercapacitors	Power dispatching	by sensing electrical quantities	by signal communication

Grid connected mode

Micro sources	Local control scheme	Organization	
Renewable Energy Based Generators	Grid-following		
Gas Microturbine	Power dispatching	by sensing electrical quantities	by signal communication
Supercapacitors	Power dispatching	by sensing electrical quantities	by signal communication

Figure V-7. Chosen local control schemes and organization of the microgrid supervision

V.6. Conclusion

Market acceptability of DER technologies and the gradual and consistent increase in their depth of penetration have generated significant interests in integration, controls, and optimal operation of DER units in the context of microgrids. In this context microgrids are a possible organization with specific details as:
- Power generators are connected with power electronic converters in our studied microgrid,
- The distances among the DER units are closed (within 100m).

A communication bus can be used without consideration of signal losses. In our proposed system, it receives the information provided by the LCs and sends the control signals of MCC to them. These exchanges of information and commands help to achieve an optimized micro grid operation.

This chapter has highlighted various approaches of operating concepts and supervision control scheme for a micro grid. The MCC must take into account specific limits of each DG unit, including type of the DG unit, cost of generation, time-dependency of the prime source, maintenance interval and environmental impacts,

Three DER units are used in our microgrid (a photovoltaic array, a micro turbine generator and a supercapacitor storage system). Their tasks are respectively specified.

An improved MCC strategy will be presented in the following chapters. Firstly, the MCC for the grid-connected mode is detailed in the next chapter and secondly the MCC for the islanded mode in the chapter VII.

Chapter VI.
Operating in a grid-connected mode

VI.1. Introduction

The grid-connected mode is a particular complex operating mode since local loads inside the microgrid have to be supplied as well as powers have to be send to the main grid (Figure VI-1). Moreover, the microgrid can also provide ancillary services for the main grid, if needed, such as the frequency regulation. So the study of the microgrid in a grid connected mode includes research studies not only on the microgrid, but also on the distribution network.

In order to manage the DER units for the grid connected-mode, a Microgrid Central Controller (MCC) is necessary. The modeling and the local controller of each DER unit have been presented in the Part I of this report. The communication bus between DERs and the MCC is supposed to be ideal; that means that the signal transmission among the communication interface is propagated without time delay. Therefore, in this chapter we will consider a central supervision and the design of the corresponding MCC is detailed.

Before focusing on the MCC, research studies especially on the modeling of the distribution network are necessary since the static and dynamic characteristic is very important for the validation (such as its reaction in respond of the microgrid behaviors). Therefore, the modeling of the distribution network will be firstly introduced. It includes a diesel group (20kV, 200kW), the HTA line, the transformer between the HTA bus and the BT bus. The total HTA loads outside the microgrid are also modeled as an equivalent passive load (Loads 2 in Figure VI-1). The extern loads can influence the distribution network as well as the microgrid power exchange (P_{mg}, Q_{mg}) by creating voltage droops or frequency fluctuations at the HTA bus etc. The coupling method at each bus will be also presented at the end of the modeling part. The Energetic Macroscopic Representation (EMR, REM in French) is used to analyze the global architecture of the system and the Causal Ordering Graph (COG, GIC in French) is used to give a detailed representation of each EMR bloc.

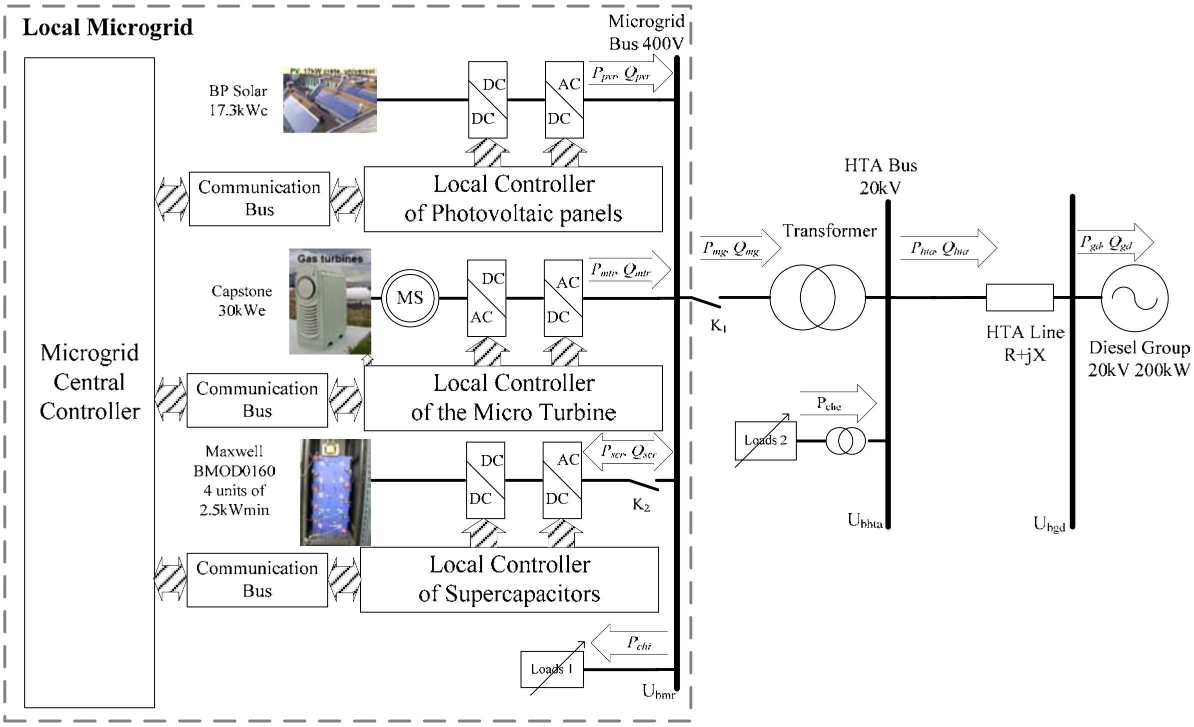


Figure VI-1. Global scheme of the studied microgrid in a grid-connected mode

Based on this modeling, the central supervision functions are designed and presented secondly. The details of each function level are given. Finally, simulation results with the help of Matlab/Simulink software will be presented to validate our proposed MCC structures.

VI.2. Microgrid modeling and the distribution network modeling

VI.2.1. Diesel group generator

In many research studies DER are connected to an infinite network, which is implemented with an ideal voltage source with a constant frequency value and a constant voltage root mean square (RMS) value [BOU-02] [LEC-04] [PAN-04]. This cannot be appropriate in the context of researches on grid-connected microgrids, especially for highlighting the participation of ancillary services, such as the primary frequency regulation. Therefore, a simplified model of a real diesel group is used with control systems of the frequency and the voltage RMS value [SAA-99] [LAW-01] [DEL-06] (Figure VI-2).

The purpose of the model is to describe mathematically the transient stability of the electrical quantities from the diesel group (such as the frequency variation or the voltage variation). So the mathematic equations are established with only variation quantities (Δ) of physical variables. The COG of the diesel group is presented at the Figure VI-3. A knowledge model (chapter I, paragraph I.2.2) using an IEEE standard has been used and is composed of four parts:

- the mechanical part;
- the voltage regulation;
- the coupling between these two parts;
- additional equations between the per units and the International System of Units (SI Units).

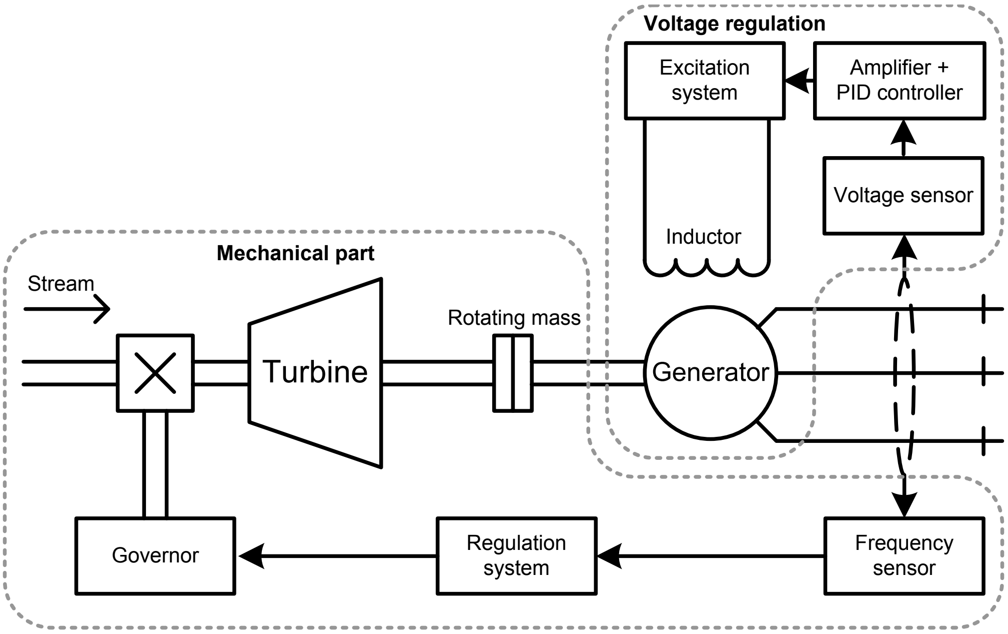


Figure VI-2. Diesel group structure

Mechanical part

The mechanical part is composed of a governor, a turbine, a rotating mass including equivalent loads, a regulation system and the power angle calculation [KUN-94] [SAA-99]. The difference between the reference and the real power is transformed through the hydraulic amplifier to the steam valve position command (ΔP_v). Assuming a linear relationship and considering a simple time constant τ_g (0.2s), the equation for the governor can be expressed as:

$$R1: \quad \Delta P_v = \frac{1}{1+\tau_g s}(\Delta P_{ref} - \Delta P_{reg}) \tag{VI-1}$$

where :

ΔP_{ref} is the change of reference real power in per unit (0, for a constant generation set point);

ΔP_{reg} is the change of the real power in per unit.

A simple prime mover model of the non-reheat steam turbine can be approximated with a single time constant τ_t (0.5s) :

$$R2: \quad \Delta P_m = \frac{1}{1+\tau_t s}\Delta P_v \tag{VI-2}$$

where ΔP_m is the change of mechanical power output in per unit.

Therefore, the speed-load characteristic (in p.u.) is approximated by considering the rotating mass and electrical load real power, which is approximately equivalent to the electromechanical power consumed by the generator (details can be found in [SAA-99] pp. 460-463 and pp. 529-568):

$$R3: \quad \Delta\omega = \frac{1}{D+2Hs}(\Delta P_m - \Delta P_c - \Delta P_e) \tag{VI-3}$$

where :

ΔP_c is the change of load real power in per unit;

ΔP_e is the change due to the effect of voltage upon real power in per unit;

H is the per unit inertial constant (5 in per unit);

D is expressed as a percent change of the load divided by a percent change in frequency (0.8

in per unit). Hence the load is changed by 0.8 percent for a 1 percent change in frequency.

The small change of the power angle ($\Delta\delta$) is obtained by integration of the small change of the speed:

$$R4: \quad \Delta\delta = \frac{1}{s}\Delta\omega \tag{VI-4}$$

The regulation system is composed of a governor speed regulation with (or without) an Automatic Generation Control (AGC), which is based on an integral controller:

$$R11: \quad \Delta P_{reg} = -(\frac{1}{R} + \frac{K_I}{s})(\Delta\omega_{ref} - \Delta\omega) \tag{VI-5}$$

where:

R is the speed regulation ratio (0.05);

K_I is the integral controller gain for the AGC (6);

$\Delta\omega_{ref}$ is the variation reference of grid frequency (0).

If the diesel group has not an AGC, the regulation system is expressed as:

$$R11': \quad \Delta P_{reg} = \frac{1}{R}\Delta\omega \tag{VI-6}$$

Organization of the modeling equations is shown on Figure VI-3.

Voltage regulation

The voltage regulation of the diesel group is composed of an amplifier, an exiter, a fourth order generator model, the calculation of the terminal voltage and a PID controller.

The amplifier is represented by a transfer function with a gain K_A (10) and a time constant τ_A (0.1s):

$$R6: \quad V_A = \frac{K_A}{1+\tau_A s}V_C \tag{VI-7}$$

V_A is the terminal voltage of the amplifier in per unit and V_C is the terminal voltage reference given by the PID controller in per unit. In the simplest form, the transfer function of a modern exciter can be modeled by:

$$R7: \quad V_F = \frac{K_E}{1+\tau_E s}V_A \tag{VI-8}$$

Where:

V_F is the terminal voltage of the exciter in per unit;

K_E is the exciter gain (1);

τ_E is a time constant (0.4s).

A fourth order generator model is used [LAW-01] [DEL-06] to obtain a better accuracy of the generator field calculation than with a simple first order generator model [WAL-96]:

$$R8: \quad E' = \frac{(1+T_{z1}s)(1+T_{z2}s)(1+T_{z3}s)(1+T_{z4}s)}{(1+T_{p1}s)(1+T_{p2}s)(1+T_{p3}s)(1+T_{p4}s)}(V_F - K_4\Delta\delta) \tag{VI-9}$$

Where :

T_{p1} (3.95) and T_{z1} (0.909) are the pole-zero time constants of the first order model,

T_{p2} (0.148) and T_{z2} (0.126) are the pole-zero time constants of the second order model,

T_{p3} (8.38×10^{-3}) and T_{z3} (6.88×10^{-3}) are the pole-zero time constants of the third order model,

T_{p4} (9.37×10^{-4}) and T_{z4} (7.75×10^{-4}) are the pole-zero time constants of the fourth order model,

K_4 is a gain.

Including the small effect of the rotor angle upon the generator terminal voltage, the generator terminal voltage can be written as [SAA-99]:

$$R9: \qquad V_t = K_5 \Delta\delta + K_6 E' \tag{VI-10}$$

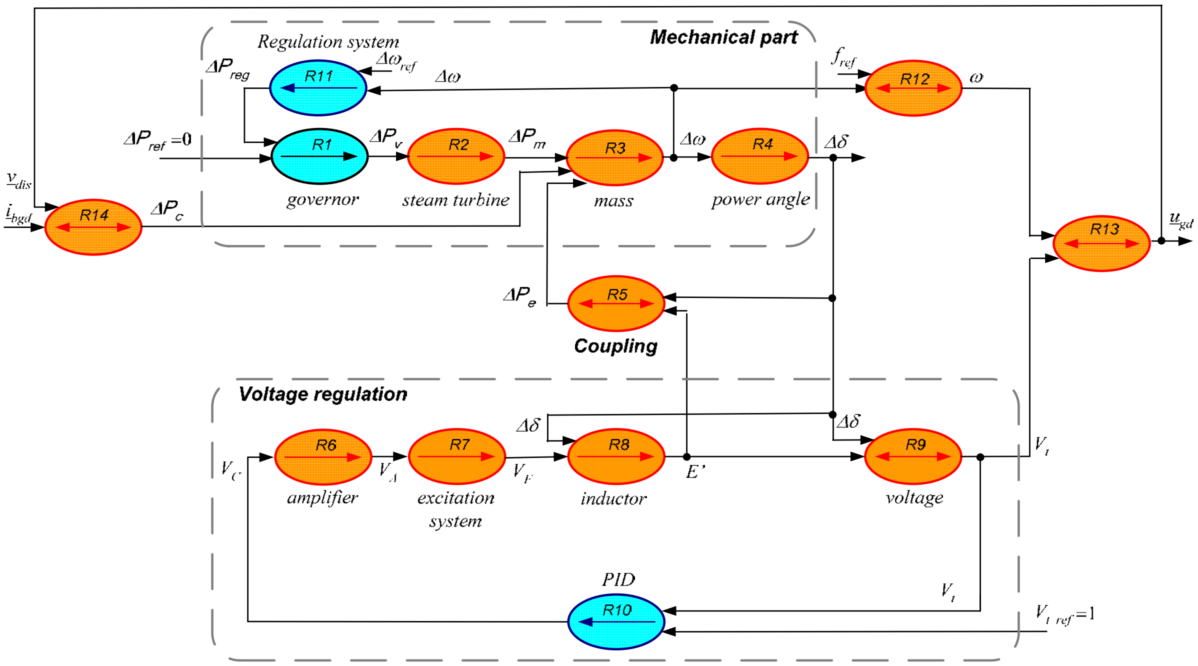


Figure VI-3. COG of the diesel group standard model

K_5 is the gain of the change in the terminal voltage for a small change in rotor angle with a constant stator emf (-0.1) and K_6 is the gain of the change in the terminal voltage for a small change in the stator emf with a constant rotor angle (0.5). A PID controller is used to improve the dynamic response as well as to reduce or eliminate the steady-state error:

$$R10: \qquad V_C = (K_{PC} + \frac{K_{IC}}{s} + K_{DC}s)V_t \tag{VI-11}$$

Where:

K_{PC} is proportional gain (3);

K_{IC} is integral gain (0.7);

K_{DC} is derivative gain of the PID controller (0.2).

Coupling between these two parts

Equations *R4* and *R5* represent the interaction between the frequency regulation and the voltage regulation. [*R4* has been introduced at the equation (VI-4)]. The small change in the real power due to the effect of voltage can be expressed as:

$$R5: \qquad \Delta P_e = P_s \Delta\delta + K_2 E' \tag{VI-12}$$

P_s is the synchronizing power coefficient in per unit (1.5) andvK_2 is the change in electrical power for a small change in the stator emf (0.2).

Adaptation between the per units and SI units

The adaptation between the per units and SI units is derived by the equations *R12*, *R13* and *R14*. The change for the grid frequency is calculated as:

$$R12: \qquad \omega_{(\mathrm{rad/s})} = 2\pi f_{ref\,(\mathrm{Hz})} + \Delta\omega_{(\mathrm{rad/s})} \tag{VI-13}$$

$$\Delta\omega_{(\text{rad/s})} = 2\pi f_{ref\,(\text{Hz})}\Delta\omega_{(\text{pu})} \qquad \text{(VI-14)}$$

where f_{ref} is the grid frequency (50 Hz).

The change from per unit to SI unit (volt) for the voltage is given as:

$$R13: \begin{cases} u_{gd13\,(\text{V})} = \sqrt{3}V_{t\,(\text{pu})}V_{tn\,(\text{V})}\sin(\omega t - \frac{1}{6}\pi + \theta_0) \\ u_{gd23\,(\text{V})} = \sqrt{3}V_{t\,(\text{pu})}V_{tn\,(\text{V})}\sin(\omega t - \frac{1}{2}\pi + \theta_0) \end{cases} \qquad \text{(VI-15)}$$

Where:

$\underline{u}_{gd} = [u_{gd13}, u_{gd23}]^T$ is the vector of phase-to-phase terminal voltages;

V_{tn} is the nominal voltage value of the diesel group;

θ_0 is the initial angle.

The change from SI units (Watt) to per unit of load power fluctuations is expressed as:

$$R14: \quad \Delta P_c = \frac{1}{P_{ngd}}(\underline{u}_{gd}^T \cdot \underline{i}_{bgd} - P_{ngd}) \qquad \text{(VI-16)}$$

P_{ngd} is the nominal generated real power by the diesel group (200 kW) and $\underline{i}_{bgd} = [i_{bgd1}, i_{bgd2}]^T$ is the vector of diesel group currents. As results, the EMR description of the diesel group is given at the Figure VI-4.

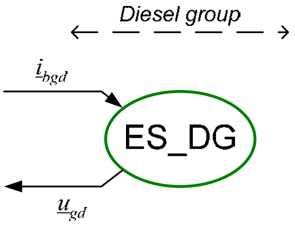


Figure VI-4. EMR of the diesel group modeling

VI.2.2. Modeling of the HTA transmission lines

Classical modeling of the HTA transmission line uses a Π model, which is composed of a resistor, a reactance and two capacitors [GAU-07] for each line (Figure VI-5 and Figure VI-6). The capacitors are neglected in this research work due to their small value and their little influence on the microgrid [ELA-04] [MOG-05].

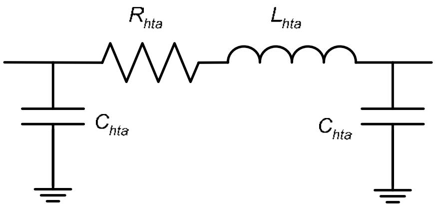


Figure VI-5. Π model of one phase of a HTA transmission line

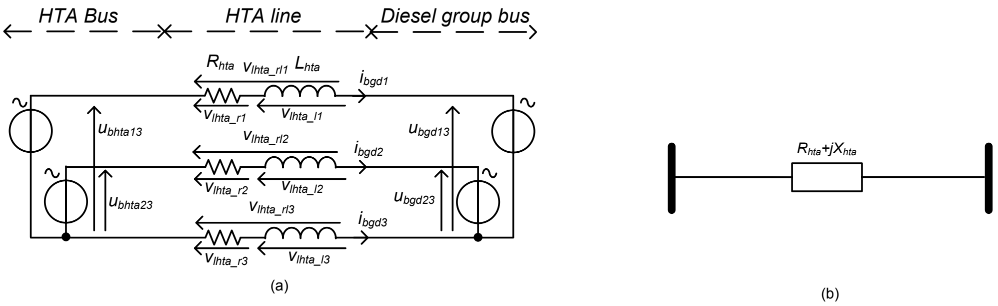


Figure VI-6. Simplified model of a HTA transmission line (a) and its equivalent symbol (b)

Therefore the modeling of the HTA transmission lines is similar to the modeling of a three phase filter, which has been presented in the chapter II :

$$Pro1: \quad \frac{d\underline{i}_{lhta}}{dt} = \frac{1}{L_{hta}}\underline{v}_{lhta\_l} \quad (R16) \tag{VI-17}$$

$$\underline{v}_{lhta\_l} = \underline{v}_{lhta\_rl} - \underline{v}_{lhta\_r} \quad (R17) \tag{VI-18}$$

$$\underline{v}_{lhta\_rl} = C_{ucs} \cdot (\underline{u}_{bgd} - \underline{u}_{bhta}) \quad (R18) \tag{VI-19}$$

$$\underline{v}_{lhta\_r} = R_{hta}\underline{i}_{lhta} \quad (R19) \tag{VI-20}$$

where

$\underline{i}_{lhta} = [i_{lhta1}, i_{lhta2}]^T$ is the vector of the HTA transmission line currents,

L_{hta} and R_{hta} are the inductor and the resistor of the HTA transmission line model,

$\underline{v}_{lhta\_l} = [v_{lhta\_l1}, v_{lhta\_l2}]^T$ is the vector of modeled inductor terminal voltages,

$\underline{v}_{lhta\_r} = [v_{lhta\_r1}, v_{lhta\_r2}]^T$ is the vector of modeled resistor terminal voltages,

$\underline{v}_{lhta\_rl} = [v_{lhta\_rl1}, v_{lhta\_rl2}]^T$ is the vector of modeled element terminal voltages,

$\underline{u}_{bgd} = [u_{bgd13}, u_{bgd23}]^T$ is the vector of phase-to-phase voltages of the diesel group bus,

$\underline{u}_{bhta} = [u_{bhta13}, u_{bhta23}]^T$ is the vector of phase-to-phase voltage of the HTA bus,

C_{ucs} is the matrix for the passage from phase-to-phase voltages to single-phase voltages (presented in the Chapter I).

The COG modeling of the dynamic quantities of a HTA transmission line is given at the Figure VI-7. The EMR modeling of HTA transmission lines is shown on the Figure VI-8.

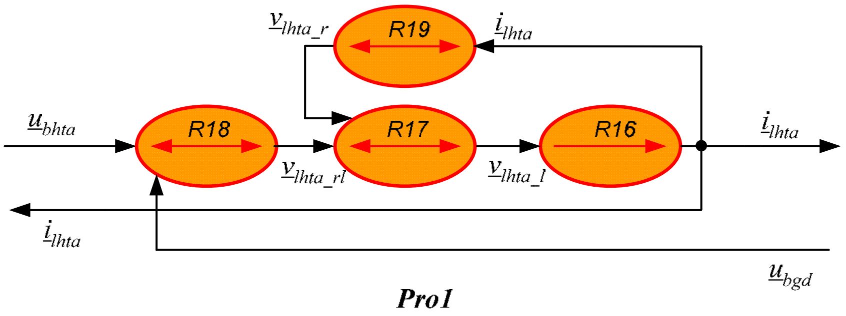


Figure VI-7. COG of the HTA the line modeling

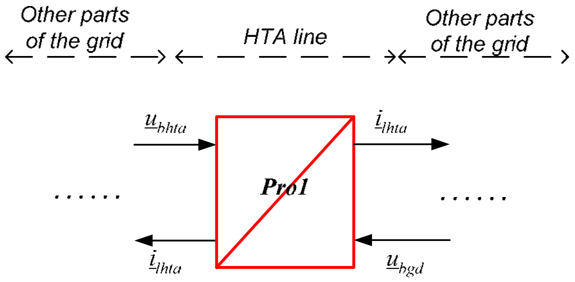


Figure VI-8. EMR of HTA lines

VI.2.3. Modeling of the three-phase transformer

Here an ideal three-phase transformer is used with a transmission ratio k_{tra} (50).

$$Pro2: \quad \underline{u}_{tra} = k_{tra}\underline{u}_{bmg} \quad (R20) \tag{VI-21}$$

$$\underline{i}_{tra} = k_{tra}\underline{i}_{bhta} \quad (R21) \tag{VI-22}$$

where:

$\underline{u}_{tra} = [u_{tra13}, u_{tra23}]^T$ is the vector of phase-to-phase voltages,
$\underline{u}_{bmg} = [u_{bmg13}, u_{bmg23}]^T$ is the vector of input phase-to-phase voltage,
$\underline{i}_{tra} = [i_{tra1}, i_{tra2}]^T$ is the vector of transformer currents,
$\underline{i}_{bhta} = [i_{bhta1}, i_{bhta2}]^T$ is the vector of input currents.

The COG and EMR modeling of the three-phase transformer is given on Figure VI-9 and VI-10.

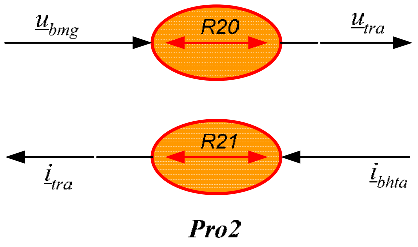


Figure VI-9. COG of the transformer

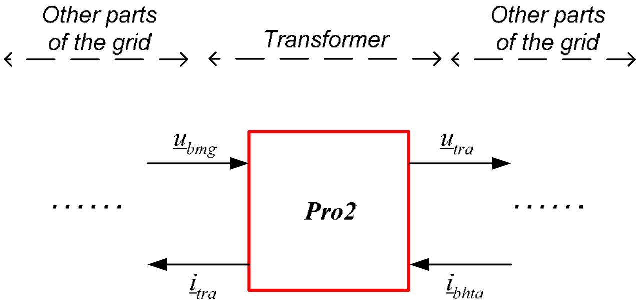


Figure VI-10. EMR of the transformer

VI.2.4. Modeling of passive loads

For the modeling of passive loads two types of model can be considered.

A "voltage receptor type" load model is considered as a voltage receptor and outputs a current to the grid (Figure VI-11). So it can be viewed also as a current-type source:

$$R22: \quad \underline{i}_{che} = \frac{1}{R_{exl}} C_{ucs} \cdot \underline{u}_{bhta} \tag{VI-23}$$

Where:

$\underline{u}_{btha} = [u_{tra13}, u_{tra23}]^T$ is the vector of phase-to-phase voltages,
$\underline{i}_{che} = [i_{che1}, i_{che2}]^T$ is the vector of load currents,
R_{exl} is the resistor corresponding to the load real power (P_{exl}).

$$R_{exl} = \frac{U^2_{nbhta}}{P_{exl}} \tag{VI-24}$$

U_{nbtha} is the nominal value of the load voltages.

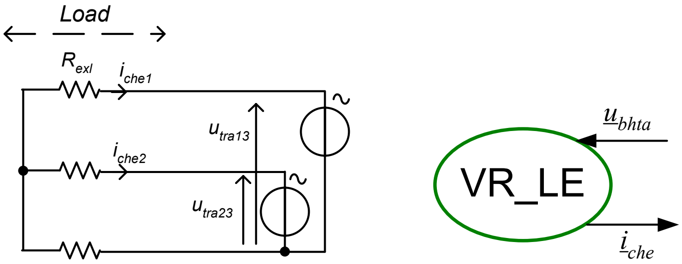


Figure VI-11. Modeling of a load as a current-type source

A "current receptor type" load model is considered as a current receptor and outputs a voltage to the grid (Figure VI-12). So it can be viewed also as a (phase to phase) "cvoltage-type source:

$$R22': \quad \underline{u}_{bhta} = C_{usc} \cdot (R_{exl}\underline{i}_{che}) \tag{VI-25}$$

where:

R_{exl} is the resistor corresponding to the load real power (P_{exl})

C_{usc} is the calculate matrix from single-phase voltages to phase-to-phase voltages (presented in the Chapter I).

$$R_{exl} = \frac{P_{exl}}{I_{nbhta}^2} \tag{VI-26}$$

I_{nbhta} is the nominal value of the load currents.

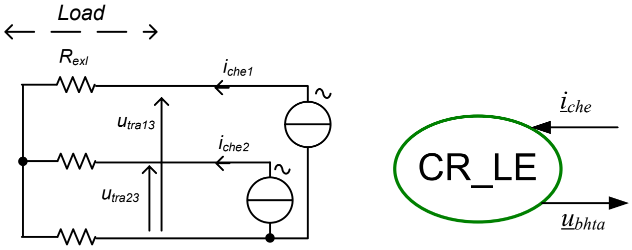


Figure VI-12. Modeling of a load as "Voltage-type" source

The choice of the model type depends on the network architecture modeling. It will be illustrated when we will model our studied network architecture.

VI.2.5. Modeling of the distribution network and the microgrid

Method

The method for modeling the grid architecture is based on the characterization of coupling bus. We have defined a design rule for the modeling: **The voltage at a bus must be set by a unique voltage-type source unit**. As result, among the various units (connected to one bus), only one unit must be a voltage-type source, the others must be considered as "current-type" sources. The architecture modeling is composed of the diesel group bus, the HTA bus and finally the microgrid bus.

Diesel group bus

At the diesel group bus, only two units are connected to it: the diesel group and the HTA lines (Figure VI-1). The diesel group is a voltage-type source since it controls its terminal voltages. Hence, the HTA lines are modeled as a current-type source:

$$Pro3:\quad \underline{i}_{lhta}=\underline{i}_{bgd} \tag{VI-27}$$

$$\underline{u}_{bgd}=\underline{u}_{gd} \tag{VI-28}$$

The EMR description of the diesel group bus is given at the Figure VI-13:

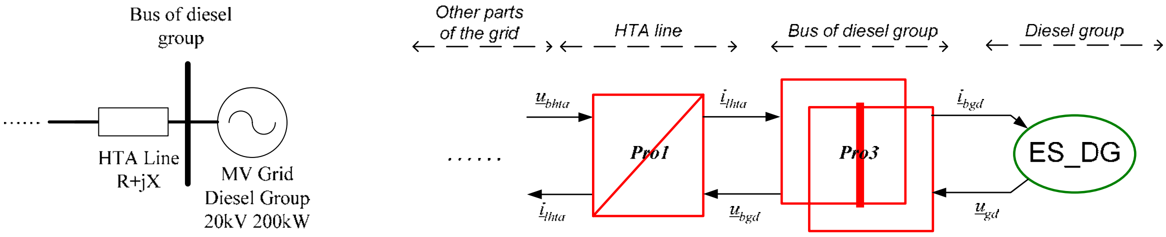


Figure VI-13. Coupling at the diesel group bus

Remark:

A bus in an EMR will be always drawn as in the Figure VI-13 in despite of the number of units, which is connected to this bus.

HTA bus

Three units are connected to the HTA bus: the HTA lines, equivalent HTA loads and the transformer (Figure VI-1). The HTA lines are current-type sources as shown in the previous analysis. Therefore, either the HTA loads or the transformer must be modeled as voltage type sources. It is interesting to choice the transformer as a voltage-type source since it is always connected to the network. This is not the case for extern loads, which are switched. Therefore, the transformer is modeled as a voltage-type source and the HTA loads as current-type sources.

$$Pro4:\quad \underline{u}_{bhta}=\underline{u}_{tra} \tag{VI-29}$$

$$\underline{i}_{bhta}=-\underline{i}_{lhta}-\underline{i}_{che} \tag{VI-30}$$

The EMR description of the diesel group bus is given at the Figure VI-14;

Microgrid bus

Many units are connected to the microgrid bus; such as the micro turbine generator, the PV generator, the supercapacitor storage system, the local loads and the transformer. As discussed previously, the transformer is modeled as a voltage-type source at the HTA line side. Therefore, it is considered as a current-type source for the microgrid bus. All DER units are connected to the microgrid bus through three-phase filters. These filters behave always as current-type sources. In consequence, local loads must be modeled as voltage-type sources at the microgrid bus. A part of local loads can be disconnected by the MCC, which must ensure the supply of critical loads.

$$Pro5:\quad \underline{u}_{bmg}=\underline{u}_{chi} \tag{VI-31}$$

$$\underline{i}_{chi}=-\underline{i}_{tra}-\underline{i}_{fmt}-\underline{i}_{fpv}-\underline{i}_{fsc} \tag{VI-32}$$

The EMR description of the diesel group bus is given at the Figure VI-15.

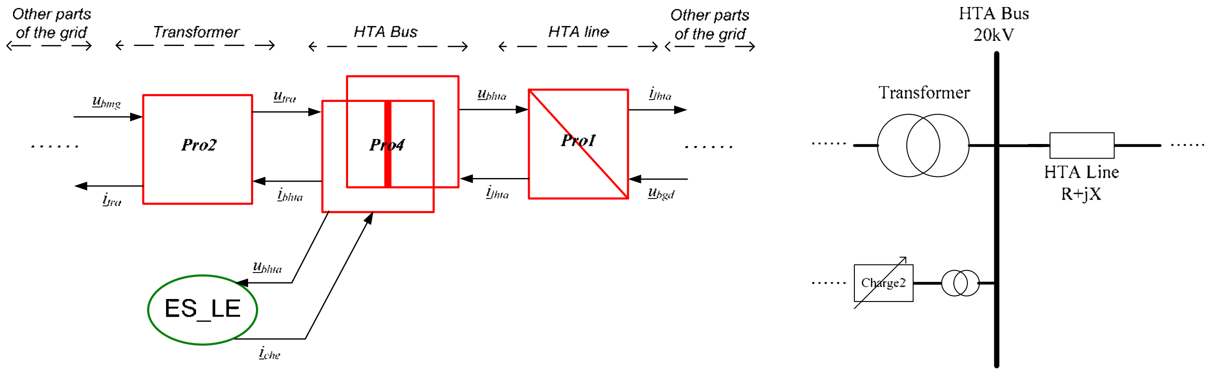


Figure VI-14. Coupling at the HTA bus

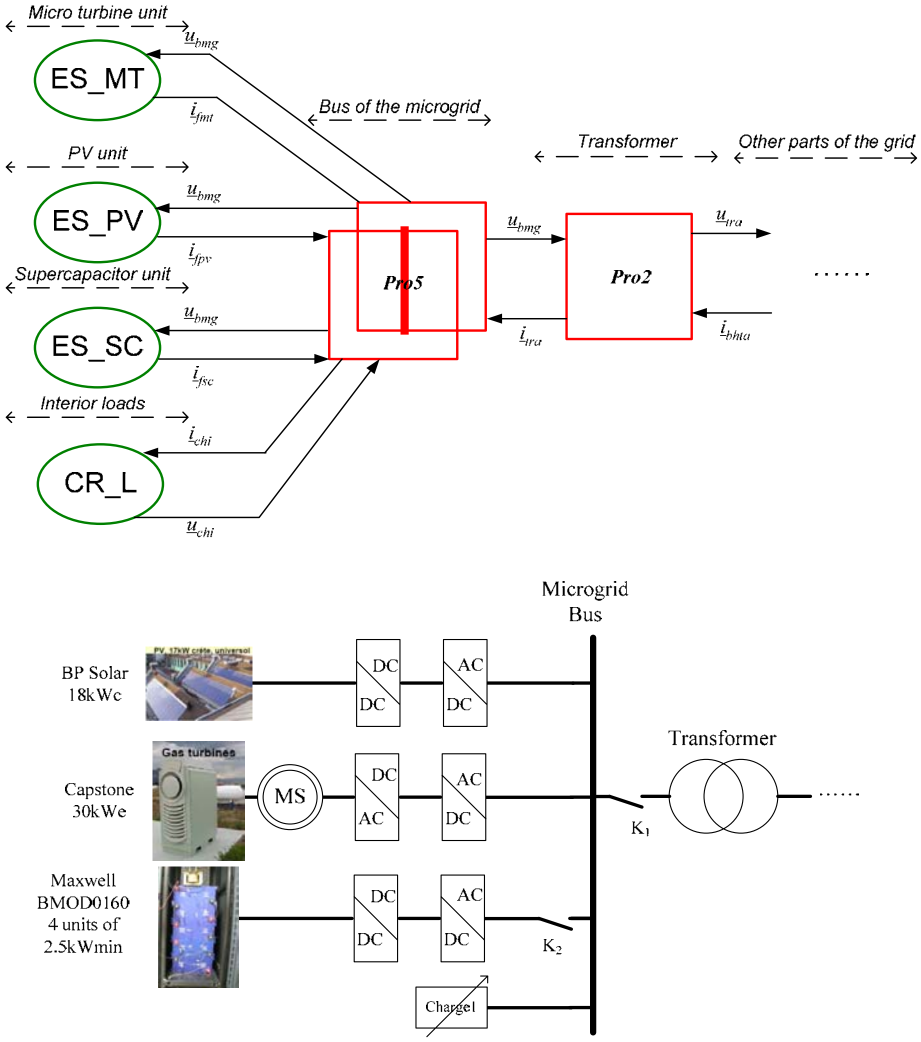


Figure VI-15. Coupling at the microgrid bus

Global architecture modeling

Finally, the global architecture modeling takes into consideration all presented EMR (Figure VI-13, Figure VI-14 and Figure VI-15) and is depicted at the Figure VI-16.

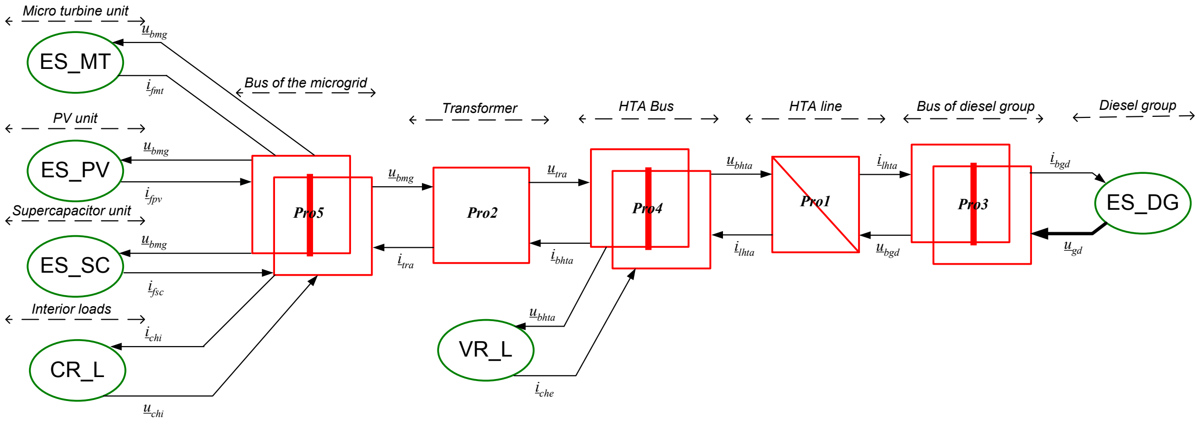


Figure VI-16. Global architecture modeling

VI.3. Microgrid Central Controller

VI.3.1. Presentation of a case study

In this part we consider a connected microgrid to a distribution grid (Figure VI-17).

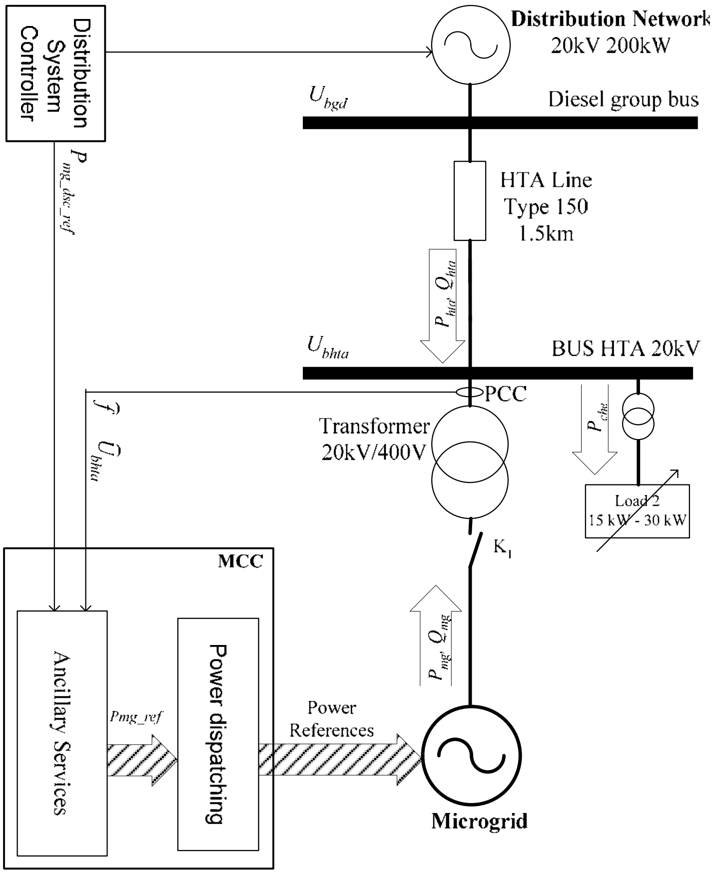


Figure VI-17. General organization of the system

For the Distribution System Operator (DSO) this local microgrid is a potential power reserve contributor. An advanced interface control system inside the MCC must be developed in order to provide the available over power in compliance with the distribution network requirement ($P_{mg\_dso\_ref}$). The bloc of ancillary services implements the grid integration and coordination of the microgrid with the distribution network system. It includes frequency and voltage control algorithms at the Point of Common Coupling (PCC) within a grid power flow assessment, protections and additional measurements.

In this paragraph, we just detail the design of the MCC for power exchange with the distribution network. First we recall the fundamental principle of the primary and secondary frequency control of the grid and then we will detail the necessary functions inside the MCC to adapt the operating of the microgrid with the distribution network.

VI.3.2. Participation to the frequency regulation

Nowadays the synchronous operation of conventional power plants and the power balance is maintained by the grid frequency control. Classically three steps are used to describe the control principle [ABU-06] [COU-08].

1st step

After a power variation, conventional power plants will immediately release or absorb the kinetic energy from their rotating mass: $E = \frac{1}{2}J\Omega^2$ with J the inertia of the machine and Ω the rotational speed of the machine. As results, the frequency changes. The response is determined by the movement equation and is called inertial response:

$$\frac{d\left(\frac{1}{2}J\Omega^2\right)}{dt} = \Delta P_m - \Delta P_c \qquad \text{(VI-33)}$$

ΔP_m is the generated power and ΔP_c is the equivalent load power. For the diesel group the load power (ΔP_c) is the sum of the microgrid power (ΔP_{mg}) and all load powers $\sum \Delta P_{co}$ and generation powers $\sum \Delta P_{go}$ outside the diesel group:

R24: $\Delta P_c = \Delta P_{mg} + \sum \Delta P_{go} + \sum \Delta P_{co}$ (VI-34)

ΔP_{dm} is the small change of the difference between the generated power from the diesel group (P_m) and the load power (P_c):

R25 : $\Delta P_{dm} = \Delta P_m - \Delta P_c$ (VI-35)

According to the equation (VI-3), the frequency variation can be expressed by neglecting the change from the voltage effect P_e as:

$$\Delta\omega = \frac{1}{D + 2Hs}\Delta P_{dm} \qquad \text{(VI-36)}$$

The small change of the frequency (Δf) can be expressed as:

R26 : $\Delta f = \frac{\Delta\omega}{2\pi} = \frac{1}{2\pi(D + 2Hs)}\Delta P_{dm}$ (VI-37)

The frequency of the grid is then expressed with the constant grid frequency (f_{ref}=50Hz):

R27 : $f = f_{ref} + \Delta f$ (VI-38)

The frequency variation can be represented with a COG (Figure VI-18).

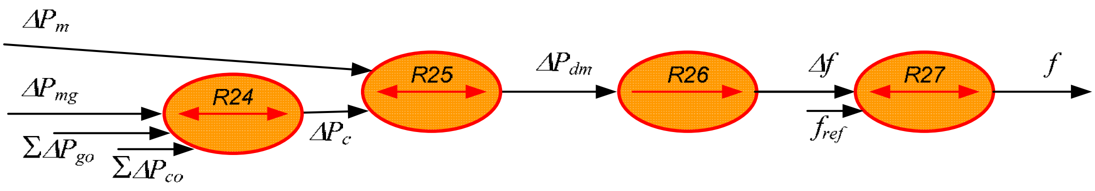


Figure VI-18. COG modeling of the frequency variation

2nd step

When the frequency deviation exceeds a pre-defined threshold value, controllers will be activated to increase or decrease the power from the prime movers to restore the power balance. The primary frequency control contribution of the generators is based on a droop constant, which gives the additional power that is supplied as a function of the frequency deviation [COU-07]. This traditional control scheme can be formalized by inversion of the relation *R26* (equation VI-37) in the COG of Figure VI-19. A proportional controller (with k_{dg} the ratio of the corrector) is often used for *R26c* :

R24c: $$\Delta P_{dm\_ref} = k_{dg}(\Delta f_{ref} - \Delta\hat{f}) = -k_{dg}\Delta\hat{f} \qquad \text{(VI-39)}$$

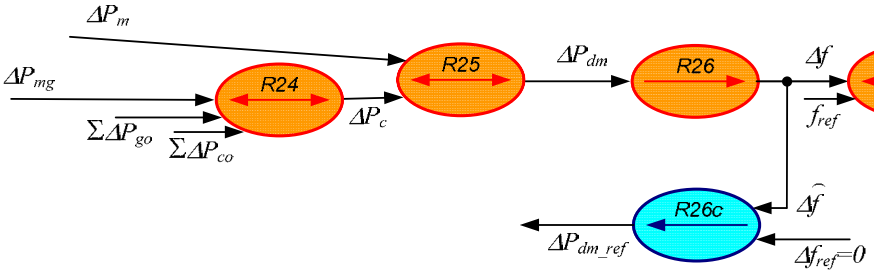


Figure VI-19. Frequency control of the diesel group

The small change of the frequency $\Delta\hat{f}$ is calculated with the sensed frequency $\hat{f}$. Therefore, the estimation of the relation *R25* is used:

R27e: $$\Delta\tilde{f} = f_{ref} - \hat{f} \qquad \text{(VI-40)}$$

ΔP_{mg_ref} and ΔP_{c_ref} must be calculated from ΔP_{dm_ref} through the inversion of relations *R24* and *R25*. Because other powers, such as $\sum \Delta P_{co}$ and $\sum \Delta P_{go}$, are difficult to sense a unique predesigned dispatching ratio (k_{dm}) is often used (Figure VI-20).

Rc: $$\Delta P_{mg\_ref} = k_{dm}\Delta P_{dm\_ref} \qquad \text{(VI-41)}$$

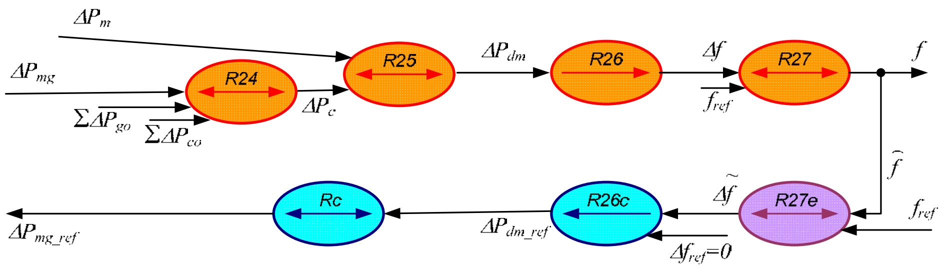


Figure VI-20. Scheme of the primary frequency control

Therefore, by combining the equations *R26c*, *R27e* and *Rc*, a traditional frequency droop control expression can be found as:

$$\Delta P_{mg\_ref} = k_{dm}k_{dg}(f_{ref} - \hat{f}) = k(f_{ref} - \hat{f}) \qquad \text{(VI-42)}$$

with $k=k_{dm}k_{dg}$ the total ratio of the participation to the primary frequency control.

As example, if the frequency changes from f_{ref} to f_1, the reference of the generated power will move from the value in normal conditions $P_{mg\_ref\_0}$ to another value $P_{mg\_ref\_1}$ (Figure VI-21).

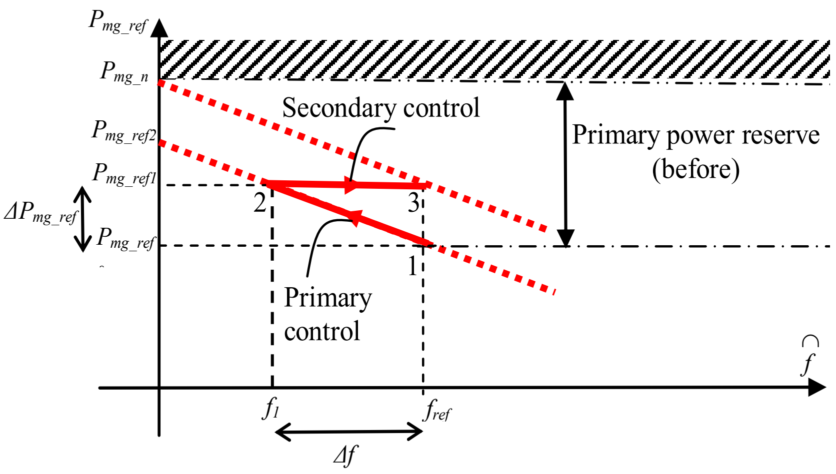


Figure VI-21. Idealized power frequency control characteristic

3rd step

After restoration of the power balance by the primary control, the system is stable (point 2 in Figure VI-21) but at another frequency (f_1). The secondary frequency control brings the frequency back to its normal value (f_{ref}) and the power operating point is changed (point 3 in Figure VI-21).

For our application, the Dispatching System Controller (DSC) sends a wished power reference $P_{mg\_dsc\_ref}$, which is considered as the exchanged power from the microgrid to the distribution network in long term (Figure VI-17). The classical power/frequency control principle has been derived inside the MCC in order to create a microgrid contribution to the primary frequency control (Figure VI-22).

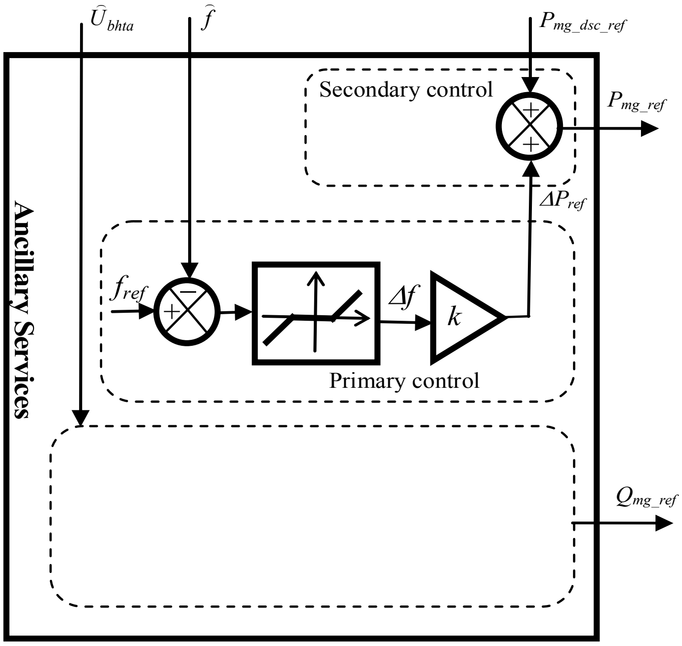


Figure VI-22. Schema block representation of the primary and secondary frequency control

The power/frequency constant is calculated with:

$$k = \frac{1}{s}\frac{P_{mg\_\max}}{f_{ref}} \tag{VI-43}$$

With the droop s (5%) and P_{mg_max} the maximum available power, which can be exported to the distribution network.

Formerly the Droop Speed Controller is derived here into a Droop Control characteristic since the three DG units play the role of an equivalent virtual prime mover.

VI.3.3. Power dispatching

The purpose of the power dispatching is to drive the three DER (PV based generator, gas micro turbine and supercapacitors in the Figure VI-1) in order to supply local loads in an optimal way for the electrical distribution and production. In this chapter, we study a microgrid application in the context of a grid-connected mode. And we are going to derive the necessary control functions (Figure V-I). For the gas micro turbine, the economic interest can be mathematically expressed as a power generation over a minimal power value. This value gives us an acceptable kW/€ ratio. In reason of their physical capacities, the supercapacitors can be used to smooth fast power variations resulting from loads and PV [DEG-06b].

The power dispatching is based on a power management whose the purpose is to implement the real time power balancing (Figure VI-23, which is an application of the Figure V-I). Before sending the dispatching power set points to each unit, some protection and regulation strategies must be added. Then calculated power references may be modified by the regulation of the operating points of DER in static state and the protection of SC storage level.

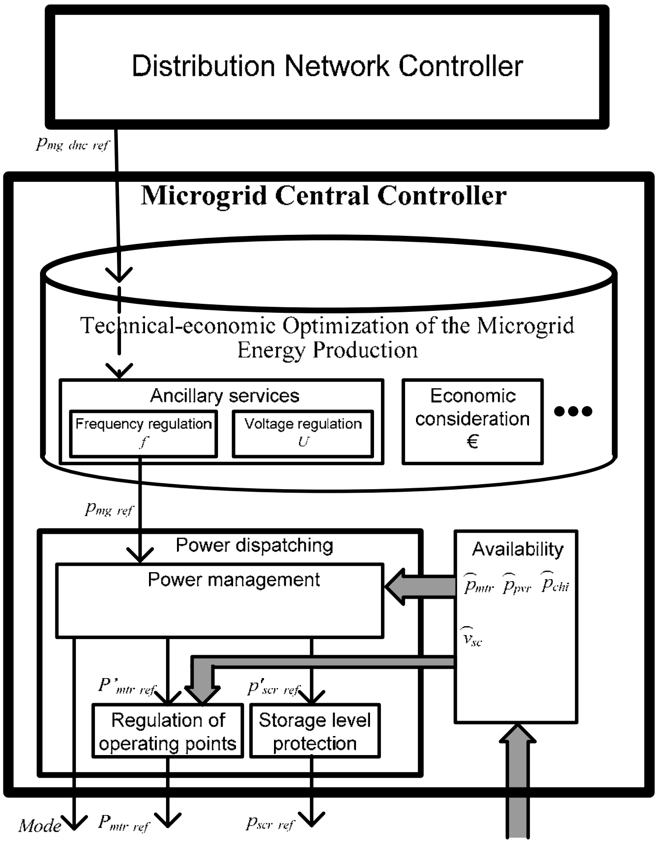


Figure VI-23. Details on the calculation of the real power in the Microgrid Central controller

VI.3.4. Power management

The balancing condition implies that the exchanged power with the distribution network has to be produced from all sources in the microgrid (Figure VI-24):

$$p_{mg}(t) = p_{mtr}(t) + p_{pvr}(t) + p_{scr}(t) + p_{chi}(t) \tag{VI-44}$$

p_{mg} is the total power of the microgrid, p_{mtr} is the power from the micro turbine, p_{pvr}, is the power from the photovoltaic generation unit, p_{scr} is the power from supercapacitors in generation mode and p_{chi} is the total consumed power by the local loads.

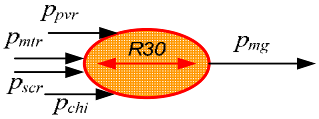


Figure VI-24. COG of the modeling of the real power flow for the microgrid bus

Since the micro turbine has a slow dynamic response time, the power management strategy is to use it to provide the power for a long time range. As explained in chapter 5, it is used to ensure the long term energy management (Figure VI-1). The average power during a time range T is expressed as:

$$P = \{ p(t) \}_T = \frac{1}{T}\int_0^T p(t)dt \tag{VI-45}$$

During such a long time range, the average value of fast power variations, which are exchanged with the supercapacitors can be neglected. The power balancing condition (VI-44) can be rewritten as (Figure VI-25):

$$R31: \quad P_{mg} = \{ p_{mg} \}_T = \{ p_{mtr}(t) + p_{pvr}(t) + p_{scr}(t) + p_{chi}(t) \}_T = P_{mtr} + P_{pvr} + P_{chi} \tag{VI-46}$$

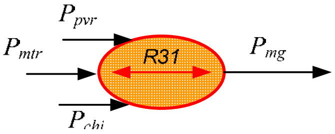


Figure VI-25. COG of the power balancing condition in a long time range

A great advantage of microgrids is the facility to use a communication bus. By assuming that the total load power ($\widehat{p}_{chi}$) and the PV generated power ($\widehat{p}_{pvr}$) are sensed and received by the MCC, the power reference for the micro turbine P'_{mtr_ref} can be calculated by the inversion of the average equation (VI-46) (Figure VI-26):

$$P'_{mtr\_ref} = P_{mg\_ref} - \widehat{P}_{pvr} - \widehat{P}_{chi} \tag{VI-47}$$

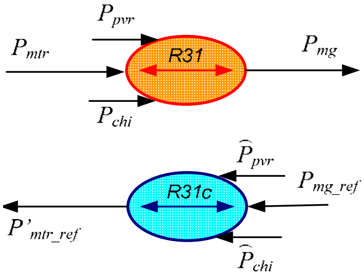


Figure VI-26. Supervision scheme of the micro turbine power reference in a long time range

The supercapacitors have the dynamic ability to master in real time fast variations of the power flow. As explained in chapter 5, it is used to ensure the short term power balancing (Figure VI-1). The power reference for the supercapacitors p'_{scr_ref} is calculated by the inversion of the real time equation (VI-44) as (Figure VI-27):

$$p'_{scr\_ref}(t) = p_{mg\_ref}(t) - \hat{p}_{mtr}(t) - \hat{p}_{pvr}(t) - \hat{p}_{chi}(t) \qquad \text{(VI-48)}$$

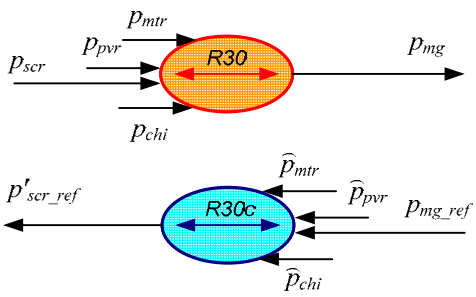


Figure VI-27. Supervision scheme of the supercapacitor power reference

This power reference is send to the local controller of the super capacitor bank (which is detailed in the Chapter IV). This one injects or absorbs in real time real power whenever the frequency deviation differs from zero.

In order to simplify the MCC for the islanded mode, the sensed power from the micro turbine can be considered equal to the reference power of the micro turbine. Therefore:

$$p'_{scr\_ref}(t) = -P'_{mtr\_ref} - \hat{p}_{pvr}(t) - \hat{p}_{chi}(t) \qquad \text{(VI-49)}$$

The power management can be described also with block diagrams (Figure VI-28) where the average power calculation is based on a low-pass filter.

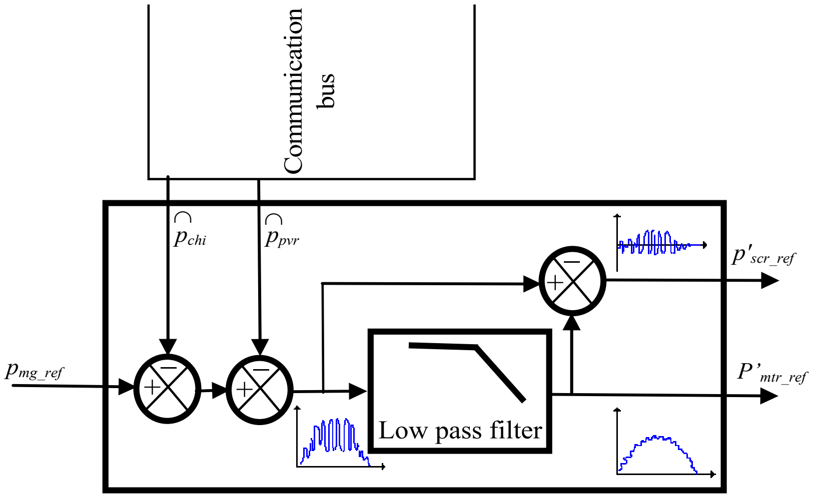
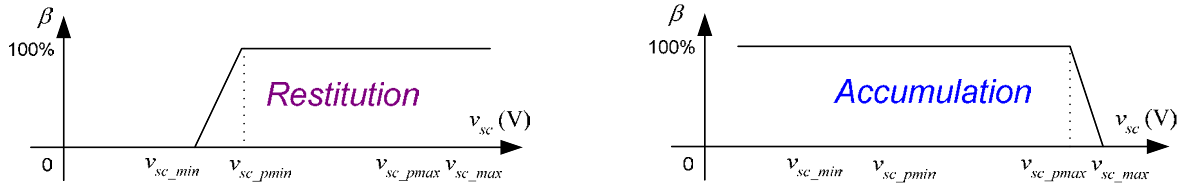


Figure VI-28. Power management

VI.3.5. Storage level protection

Supercapacitors have a finite storage capacity. The terminal voltage of the supercapacitors represents its energy storage level. For security reasons, it should be between the maximum allowed value (which represents the maximum storage energy E_{sc_max}) and 50% of this value (which represents the minimum storage energy E_{sc_min}) for efficiency reasons. In order to limit the terminal voltage, an additional control function has to be used. For example, if this voltage is under V_{sc_pmin} (105V for four supercapacitor modules in series, which represents 30% of the maximum storage energy), the available energy for generation decreased in a linear manner (Figure VI-29.a). And if this voltage is under V_{sc_min} (96V, which represents 25% of the maximum storage energy), the supercapacitors can not operate in a generation mode (Figure VI-29.a). The limitation mode for the accumulation mode is designed in a same way (Figure VI-29.b).



(a) restitution mode

(b) accumulation mode

Figure VI-29. Energy limitation for the SC storage level

The following general mathematical form is used:

$$p_{scr\_ref} = \beta \, p'_{scr\_ref} \tag{VI-50}$$

with

$$\beta = \begin{cases} 0 & \text{for} \quad \hat{v}_{sc} < v_{sc\_min} \\ \dfrac{\hat{v}_{sc} - v_{sc\_min}}{v_{sc\_pmin} - v_{sc\_min}} & \text{for} \quad v_{sc\_min} < \hat{v}_{sc} < v_{sc\_pmin} \\ 1 & \text{for} \quad v_{sc\_pmin} < \hat{v}_{sc} < v_{sc\_pmax} \\ \dfrac{v_{sc\_max} - \hat{v}_{sc}}{v_{sc\_max} - v_{sc\_pmax}} & \text{for} \quad v_{sc\_pmax} < \hat{v}_{sc} < v_{sc\_max} \\ 0 & \text{for} \quad v_{sc\_max} < \hat{v}_{sc} \end{cases} \tag{VI-51}$$

This power reference is sent to the local controller of the supercapacitor unit (which is detailed in the Chapter IV, Figure IV-30).

VI.3.6. Regulation of operating points

Another task of the power management is to supervise the storage level of the supercapacitors. If its level reaches a high level, a reduction of the generated power by the micro turbine can be used. Hence more power will be extracted from the SC and will reduce the stored energy. So the stored energy is first estimated.

$$\tilde{e}_{sc}(t) = \int_{\Delta t} \Delta p_{scr}(t)dt = \frac{1}{2} C \hat{v}_{sc}^2 \tag{VI-52}$$

Hence the micro turbine power adjustment is calculated to minimize the difference between this value and an energy level to achieve (e_{sc_ref}).

$$\Delta P_{mtr\_ref}(t) = k_{pe}\left(e_{sc\_ref} - \tilde{e}_{sc}(t)\right) \tag{VI-53}$$

So equation (VI-47) is modified to regulate the storage level v_{sc}.

$$P_{mtr\_ref}(t) = P'_{mtr\_ref}(t) + \Delta P_{mtr\_ref}(t) \tag{VI-54}$$

This power reference is sent to the local controller of the micro turbine (which is detailed in the Chapter III, Figure III-16).

The presented control strategy is integrated into the MCC and the global structure of the studied MCC is presented at Figure VI-23.

VI.4. Case study

To highlight possible contributions of the microgrid we consider a load variation in the distribution network (Figure VI-30).

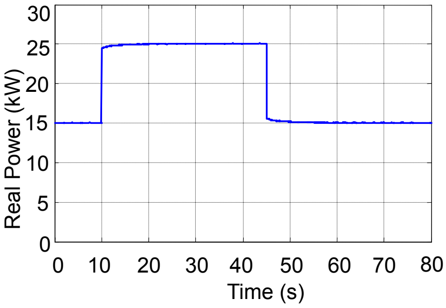


Figure VI-30. P_{che} , power from the load2

First the microgrid is disconnected to the distribution network (K_1 is open in Figure VI-1) and the reactive power (Q_{bhta}) is set to zero. Verification has been done with Matlab-Simulink^{TM} simulation tool. Obtained simulation results on Figure VI-31.a shows the frequency variations, which are caused by the load variation. Figure VI-31.b presents the power production and distribution inside the network at the PCC. Without the microgrid utility, this power is equal to the power, which is required by the load2. Currents in HTA lines (Figure VI-31.c) induce losses.

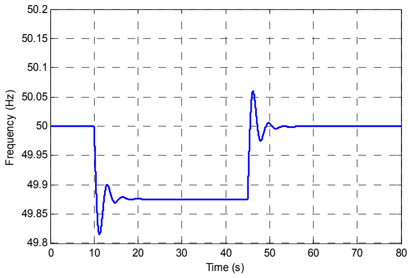
In a second time, we consider that the micro grid is connected and that the DSC asks a change of the spinning power reserve 20 seconds after the load transient (at 30s and 65s in the Figure VI-32.d). This power reserve is used to participate in the secondary frequency regulation. By comparison we can see that the frequency deviation (Figure VI-32.a) and the power inside the distribution network (Figure VI-32.b) are less. Especially at the Figure VI-32.a, the two intervals between time 10s-30s and 45s-65s show the contribution of the primary frequency control. The time intervals between 30s-45s and 65s-80s highlight the interests of the secondary frequency regulation. In consequence, currents in HTA lines (Figure VI-32.c) have been decreased.

Obtained real time variations of powers from the Gas Micro Turbine (GMT) (p_{mtr}), the supercapacitors (p_{scr}) and PV generating system (p_{pvr}) are shown on Figure VI-32.e. The PV system produces an intermittent power; the GMT matches the power requirements in a long time range; and the supercapacitors system performs the transient power management. Figure VI-32.f shows a good contribution of the microgrid both for primary and secondary frequency control. Figure VI-32.g represents the variation of the supercapacitor terminal voltage (v_{sc}). This voltage is well controlled between its limits v_{sc_max} and v_{sc_min}. In consequence, the supercapacitor storage energy varies between E_{sc_max} (nominal energy, 330 kJ) and E_{sc_min} (25% of the nominal energy) (Figure VI-32.h).

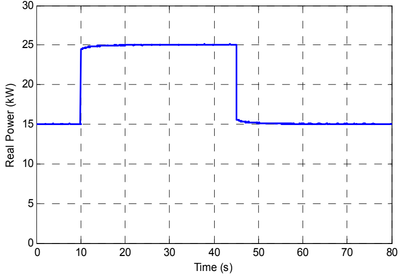
VI.5. Conclusion

The main idea of this chapter is to present an advanced microgrid central controller for a microgrid in a grid connected- operating mode.

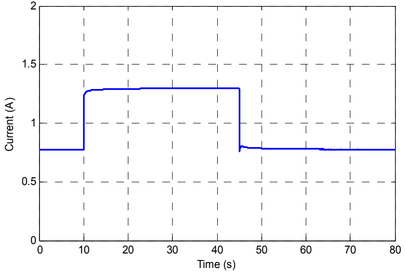
In order to achieve the design of this MCC, the modeling of a group diesel, the elements of the distribution network (three-phase filter, transformer and passive loads) and its architecture are firstly presented. An EMR and COG based knowledge modeling enables an easy integration into a simulation program with Matlab/Simulink^{TM}.



(a) frequency

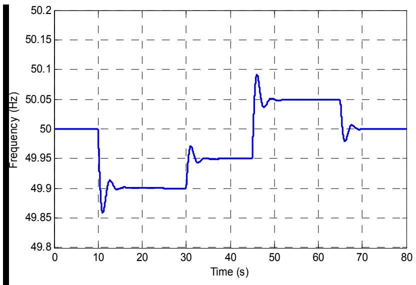


(b) P_{bhta}

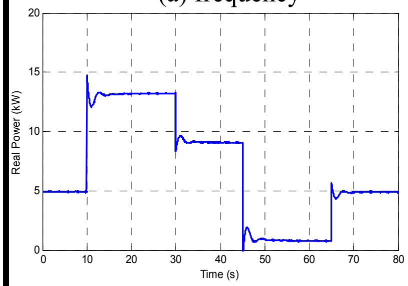


(c) Currents (in HTA lines)

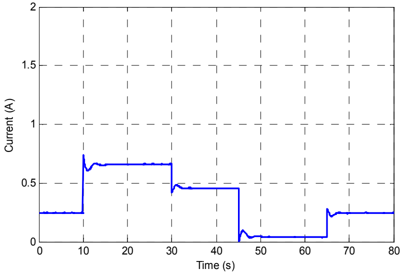
Figure VI-31. Without microgrid interactivity



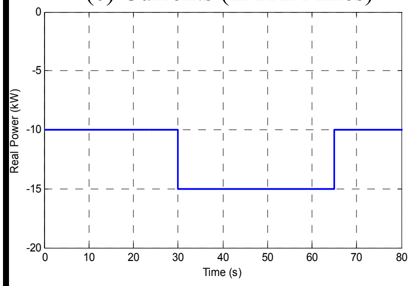
(a) frequency



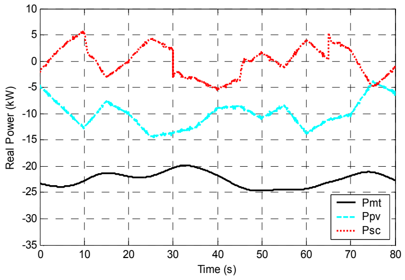
(b) P_{bhta}



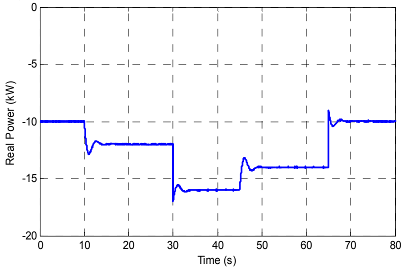
(c) Currents (in HTA lines)



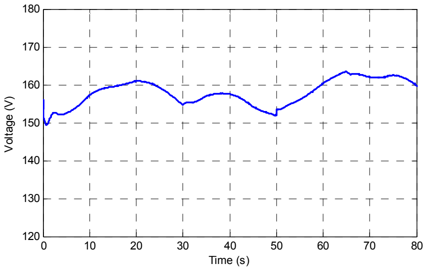
(d) $P_{mg\_dsc\_ref}$



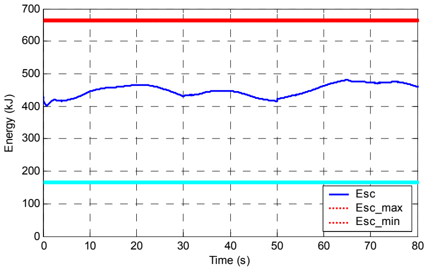
(e) Powers from sources inside the MG



(f) Injected power at the PCC



(g) Supercapacitor terminal voltage



(h) Supercapacitor storage energy

Figure VI-32. With microgrid interactivity

Secondly, a droop controller for the ancillary services and the power management with the distribution network are detailed. The MCC can control the studied microgrid to participate to the primary frequency control and a secondary frequency control is performed with the power reference sent by DSC. The power management function of the MCC calculates the power references for all controllable units within the studied microgrid. It adequately uses the gas micro turbine as a slow-response DG unit and supercapacitor units as fast-acting sources. Hence with the proposed solution a frequency variation leads automatically to a power sharing of all microgrid generators. The storage level protection and the regulation of operating points for the supercapacitor units are also presented to get an optimized operating of the supercapacitors within energy limits.

Finally, simulation results interest issues for the distribution network and validate the proposed MCC design.

Chapter VII.
Operating in an islanded mode

VII.1. Introduction

The islanded mode is another operating mode of microgrids. This mode is applied in certain situations, such as:

- the distribution network is not properly operating, for example, a black-out, an abnormal frequency or voltage variations etc.;
- the microgrid operates always without a distribution network in a local region; for example, an island or a residential zone amidst a desert etc., which are far away from a distribution network;
- the application of a commercial contract between the microgrid and the distribution network do not imply power exchange during a time interval

The local generations must fully supply local loads without surplus. In this operating mode, the MCC must correctly balance the produced power and the consumed power in the microgrid. It must also well control the microgrid voltage.

Therefore, the modeling of the studied microgrid will be firstly presented, since it is always necessary for MCC designs. Hence the control strategy of MCC will be detailed and is composed of a power dispatching function and the storage level protection and regulation. In order to validate this MCC design, some tests are achieved by using two types of devices for the microgrid: real devices (such as supercapacitor storage system and passive loads) and virtual devices, which are simulated by a real-time simulator Hypersim and interfaced with the microgrid by an amplifier (such as the micro turbine system and the photovoltaic system). The results of HIL tests will be finally presented.

VII.2. Modeling of the microgrid in islanded mode

When the microgrid operates in islanded mode, the modeling of the microgrid must take into account only the production units, the storage unit and loads within the microgrid. So we consider the micro turbine unit (presented in the Chapter III), the photovoltaic panels (presented in the Chapter IV), the supercapacitor storage unit (presented in the Chapter IV) and the local passive loads. The architecture modeling of the microgrid is achieved by considering only the microgrid bus. The principle of architecture modeling is the same as our analysis in the paragraph VI.2.5. We apply again the following modeling rule : the voltage at a bus must be set by a unique “voltage-type source” unit. All production units and the storage unit are connected at the microgrid through three-phase filters. Therefore, they are considered as current-type sources for the modeling of the microgrid bus. So the local loads must be modeled as voltage-type sources for the microgrid bus modeling. The EMR representation is given at the Figure VII-1.

The DER units are connected in parallel at the microgrid bus. So the load terminal voltage $\underline{u}_{chi}$ imposes the microgrid voltage $\underline{u}_{bmg}$ (equation (VII-1)). The currents of all DER units are calculated by the Kirchhoff’s current law. (equation (VII-2)).

Pro1: $$\underline{u}_{bmg} = \underline{u}_{chi} \quad \text{(VII-1)}$$

$$\underline{i}_{chi} = -\underline{i}_{mtr} - \underline{i}_{pvr} - \underline{i}_{scr} \quad \text{(VII-2)}$$

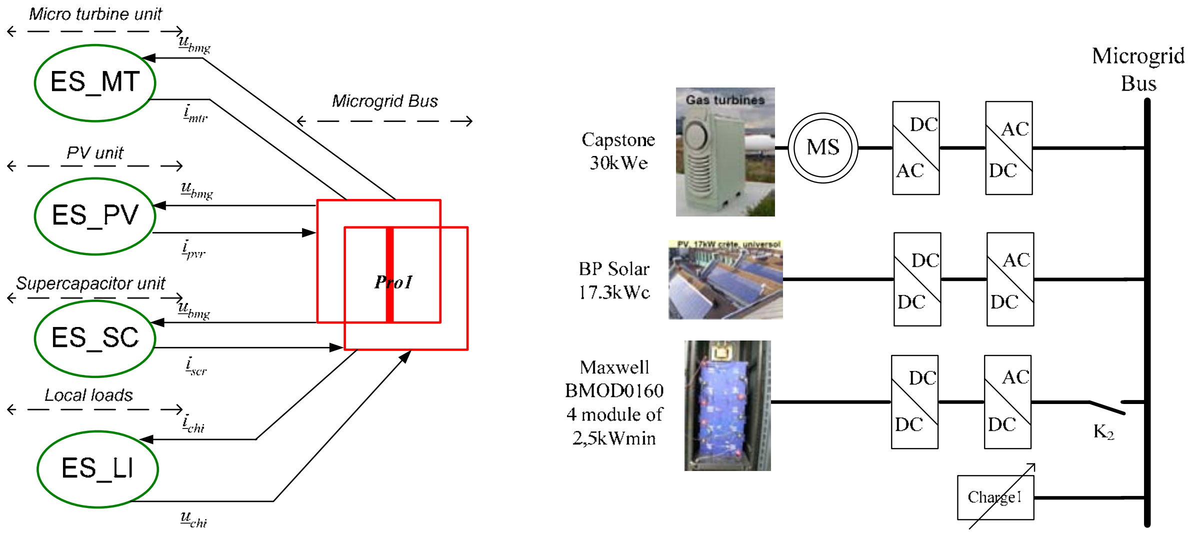


Figure VII-1. Global architecture modeling

VII.3. MCC design

VII.3.1. Introduction

The framework of the microgrid system has been explained in chapter V (paragraph V.5). In order to define the operating objective of each DER units, the following considerations must be taken into account.

Firstly, the microgrid voltage in islanded mode must be controlled by a controllable source. Therefore, the micro turbine has been chosen for the control of this voltage and for assuming the long term energy management. The supercapacitor unit is also a controllable source. It is used to perform the short-time power balancing. The microgrid voltage can not be controlled any longer when there is no more supercapacitor stored energy.

Secondly, by receiving the information given by the DER units, the MCC calculates the set point of the supercapacitor, since it manages the power in short-time range. By setting a correct power reference for supercapacitor unit, the operating of the micro turbine can be well stabilized. In consequence the gas injection is expected to be more continuous. That increases the lifetime of the micro turbine and the economic consideration for the gas consumption.

Therefore, the controls of DER units can be given as:

- For the photovoltaic panels, the PV is operated in Maximum Power Point Tracker (MPPT) mode in order to generate as much as possible, since its primary source (the sun irradiation) is free. Therefore the power production from PV unit is intermittent according to the climatic conditions. The information of the produced power is transmitted to the MCC.
- The microturbine is controlled with a « Grid-forming control scheme » (paragraph III.4) to regulate the microgrid voltages (chapter V, paragraph V.5). Although the power dispatching function of the MCC calculates the power references for the microturbine, those references are not communicated to the micro turbine.
- The power dispatching function of the MCC calculates the power reference for the supercapacitor unit. Therefore it can smooth the power during the transient variations and

balance in real time the power.

The details of calculation will be presented in the following paragraph.

VII.3.2. Power dispatching

The power dispatching function calculates the real power reference for the SC unit (p_{scr_ref}) in islanded mode. To achieve this goal, we must firstly model the power flow within the microgrid.

Without the connection to the distribution network, the islanded mode implies a balance between loads and generators. Actually, the modeling of power flow does not change from the one which is presented in the chapter VI if the exchanged power with the distribution network (p_{mg}) is set to zero. The GIC of the power modeling is shown on Figure VII-2.

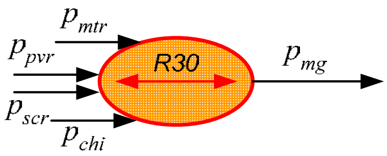


Figure VII-2. Modeling of the microgrid power flow

According to the equation *R30* in the chapter VI and by supposing $p_{mg} = 0$, we get :

$$R30 \qquad p_{mtr}(t) + p_{pvr}(t) + p_{scr}(t) + p_{chi}(t) = p_{mg}(t) = 0 \tag{VII-3}$$

p_{mtr} is the real power, which is injected by the micro turbine unit. p_{pvr} is the real power, which is injected to the microgrid by the photovoltaic unit. p_{mtr} is the real power, which is exchanged with the supercapacitor storage unit. p_{chi} is the local loads power. During a long-time range, the power balance equation can be rewritten as (same modeling for the slow dynamic than the chapter VI):

$$\{p_{mtr}(t) + p_{pvr}(t) + p_{chi}(t)\}_T = \{p_{mg}(t)\}_T = 0 \tag{VII-4}$$

$$P_{mtr} + P_{pvr} + P_{chi} = P_{mg} = 0 \tag{VII-5}$$

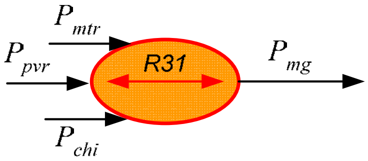


Figure VII-3. Real power balance in a long-time range

For the MCC design, the power dispatching function does not change if the reference value of the exchanged power with the distribution grid is zero ($p_{mg\_ref} = 0$). The power from the local loads and the photovoltaic generator are considered as disturbances. Therefore, the reference power for the micro turbine p_{mtr_ref} can be calculated by the inversion of the model in a long time range (Figure VII-4):

$$R31c \qquad P'_{mtr\_ref} = P_{mg\_ref} - \widehat{P}_{pvr} - \widehat{P}_{chi} = -\widehat{P}_{pvr} - \widehat{P}_{chi} \tag{VII-6}$$

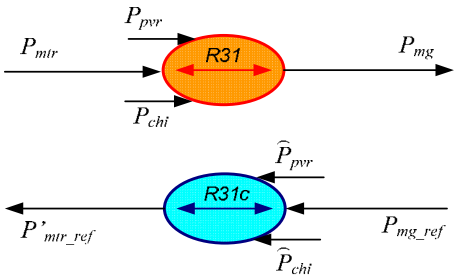


Figure VII-4. Power dispatching for the real power reference of the micro turbine

A discussed before, for the microgrid islanded mode, it is useless to send a power reference to the micro turbine since the micro turbine works in a « Grid-forming control scheme ». Therefore, this power reference is just used as internal information for the MCC.

The supercapacitors are a fast dynamic device to control in real time fast variations of the power flow. As explained in chapter 5, it is used to ensure the short term power balancing (Figure V-1). The real time power reference p'_{scr_ref} is calculated by the inversion of the timing model:

$$p'_{scr\_ref}(t) = p_{mg\_ref} - \widehat{p}_{mtr}(t) - \widehat{p}_{pvr}(t) - \widehat{p}_{chi}(t) = -\widehat{p}_{mtr}(t) - \widehat{p}_{pvr}(t) - \widehat{p}_{chi}(t) \qquad \text{(VII-7)}$$

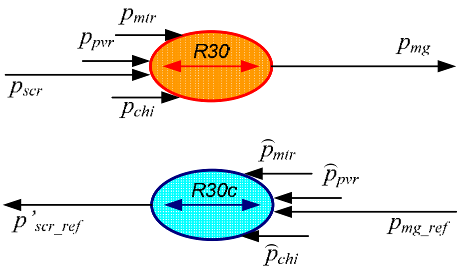


Figure VII-5. Power dispatching calculation for the real power reference of the SC

In order to simplify the MCC for the islanded mode, the sensed power from the micro turbine can be considered equal to the reference power of the micro turbine. Therefore:

$$p'_{scr\_ref}(t) = -P'_{mtr\_ref} - \widehat{p}_{pvr}(t) - \widehat{p}_{chi}(t) \qquad \text{(VII-8)}$$

Therefore we find a schema bloc for the real power dispatching by imposing $p_{mg\_ref} = 0$ (Figure VII-6). So the same dispatching is used and is modified in inputs and outputs in order to implement the grid connected mode (GM) and the islanded mode (IM).

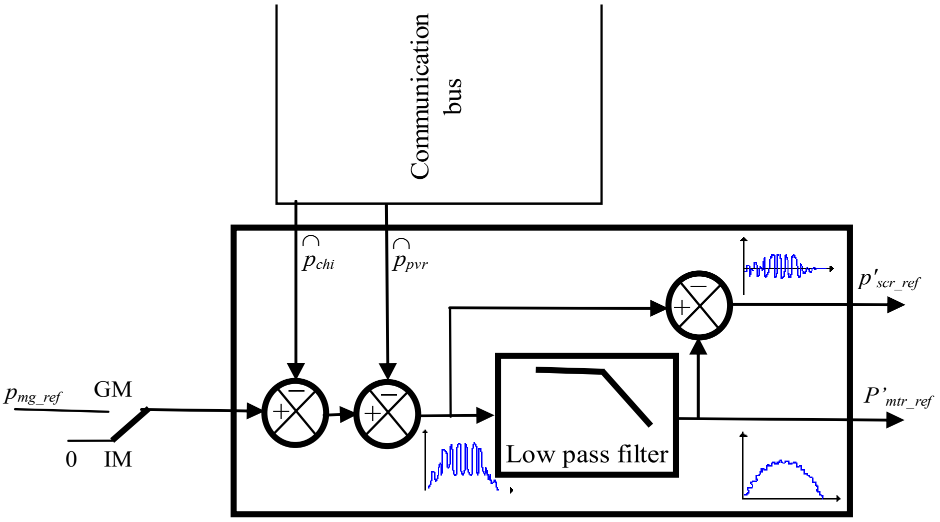


Figure VII-6. Power dispatching

VII.3.3. Protection of the storage level

The protection of the storage level of the supercapacitors has been presented in the chapter VI (paragraph VI.3.5). In this chapter, before sending the power references to the local controllers, we have added the same protection function to modify the power reference if necessary. The following general mathematical form is used:

$$p_{scr\_ref} = \beta \; p'_{scr\_ref} \tag{VII-9}$$

with

$$\beta = \begin{cases} 0 & \text{for} \quad \hat{v}_{sc} < v_{sc\_min} \\ \dfrac{\hat{v}_{sc} - v_{sc\_min}}{v_{sc\_pmin} - v_{sc\_min}} & \text{for} \quad v_{sc\_min} < \hat{v}_{sc} < v_{sc\_pmin} \\ 1 & \text{for} \quad v_{sc\_pmin} < \hat{v}_{sc} < v_{sc\_pmax} \\ \dfrac{v_{sc\_max} - \hat{v}_{sc}}{v_{sc\_max} - v_{sc\_pmax}} & \text{for} \quad v_{sc\_pmax} < \hat{v}_{sc} < v_{sc\_max} \\ 0 & \text{for} \quad v_{sc\_max} < \hat{v}_{sc} \end{cases} \tag{VII-10}$$

Therefore, the global MCC can be detail as the Figure VII-7.

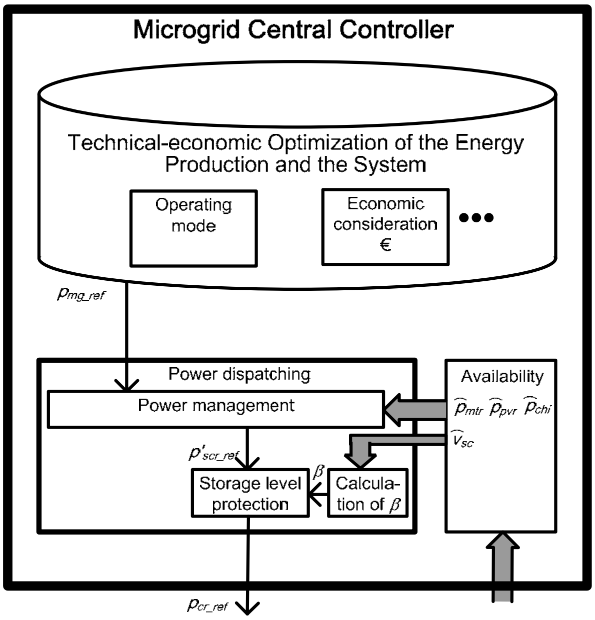


Figure VII-7. Studied Microgrid Central controller

VII.4. Hardware-In-the-Loop Test studies

VII.4.1. Introduction of the test environment

The objective is to validate the MCC by a Hardware-In-the-Loop (HIL) test and to show the advantage of a supercapacitor unit in islanded mode. The HIL scenario is presented at the Figure VII-8. Test devices are divided into two classes: the microgrid devices (the DER units, loads etc.) and the control devices (the LCs, the MCC etc.).

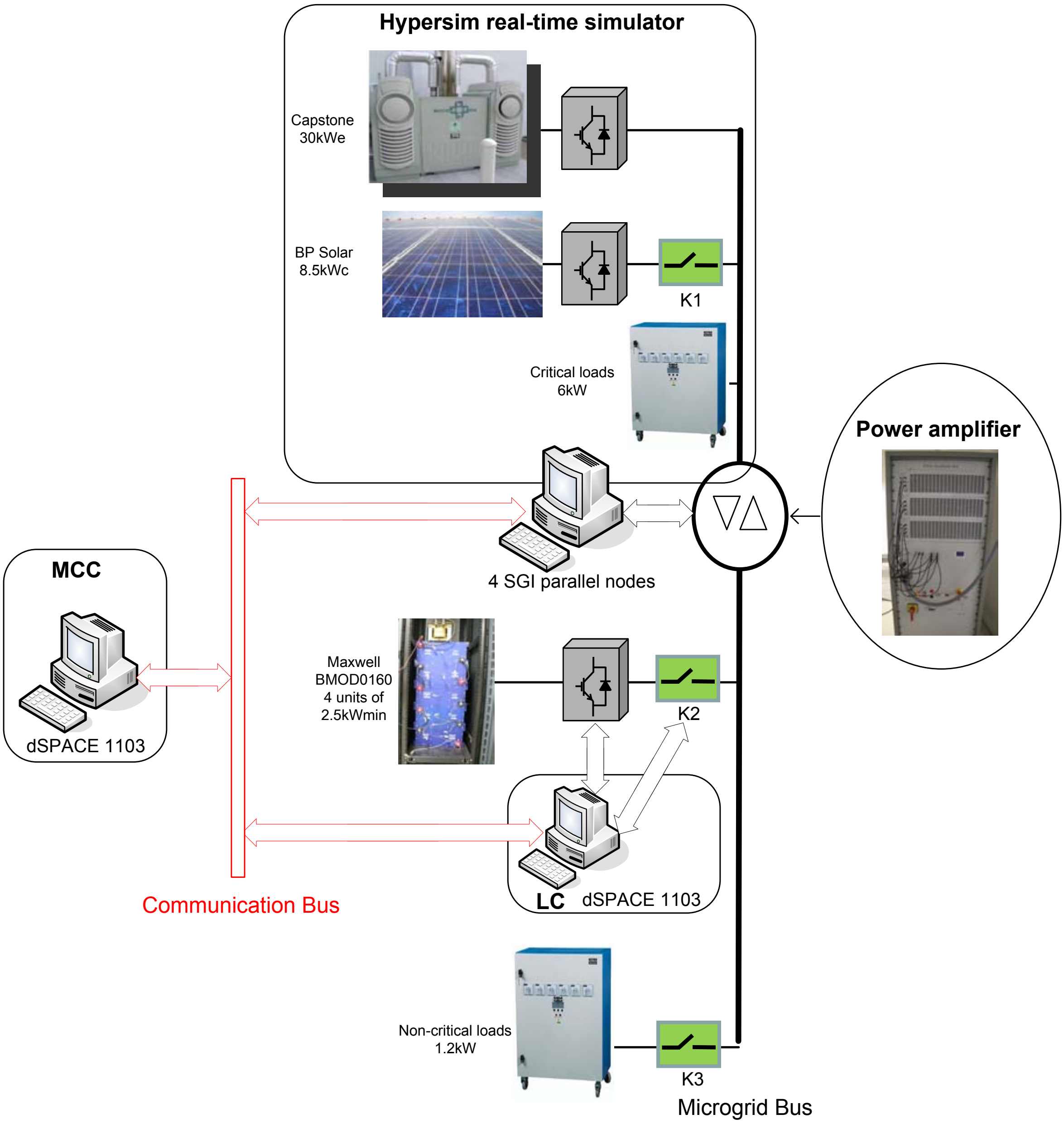


Figure VII-8. HIL test set up

Three types of devices are used:

- Real devices, which include a supercapacitor unit and 1.2 kW passive loads. It has been already presented in the Chapter IV. Passive load devices represent non-critical loads. During the test, a load step is created by switching them;
- The virtual devices are simulated under the real-time simulator Hypersim. It includes the micro turbine generator, the PV unit and the 6kW passive loads. Passive loads represent the critical loads and must remain connected to the microgrid during the test. The micro turbine unit controls the microgrid voltage and the PV unit provides an intermittent power according the sensed irradiance and the sensed temperature.
- A bidirectional power amplifier, which is used for the interface with the virtual Hypersim microgrid bus and the real microgrid bus. The amplifier imposes the voltage for the microgrid and senses the feed-back current to the Hypersim real time simulator. Thus, the fictive devices react with this feed-back current. It can nominally provide 15 kW real power to the microgrid or

receive 3 kW real power from the microgrid.

The control devices are composed of four parts:

- The MCC is implemented in a dSPACE 1103 card. It communicates with the LCs;
- Another dSPACE 1103 is used to implement the LC of the supercapacitor unit;
- The LCs of the micro turbine unit and the PV unit are integrated into the Hypersim software simulator;
- The communication bus exchanges the signals between the MCC and LCs. In this work, we use electrical cables for this communication bus.

The detail of the communication signals is presented at the Figure VII-9. PV generator, SC unit and non critical loads can be connected, disconnected to the microgrid by closing/ opening a circuit breakers.

The MCC sends the On/Off state signal to the LC of the micro turbine unit to start/stop its operating. The micro turbine returns its On/Off state as a confirmation. At the meantime, the micro turbine sends its sensed power to the MCC.

The MCC exchanges the On/Off state with the LC of PV. Since the PV generates its MPPT power, it sends its sensed power to the MCC.

The MCC sends the On/Off state signal to the LC of the supercapacitor unit to start/stop its operating. Secondly, the MCC sends the control signal for the real power exchanged with the supercapacitor unit. The SC returns its sensed real power as information. In the meantime, the LC sends the supercapacitor terminal voltage to the MCC as the information of the storage level.

Beside the signals mentioned above, the MCC also must get the information of the loads, such as the power P_{lt} from the real load device and the power P_{lf} from the fictive load device into Hypersim. The total local load power P_{chi} is the sum of those two powers.

VII.4.2. Test procedure

The load power is defined as positive and produced powers are negative. 6kW critical loads remain connected and have to be supplied. The microgrid voltage is controlled to 400V by the micro turbine. HIL test results are presented with the following acronyms:

- MT : Micro Turbine unit (fictive, under Hypersim),
- PV : PhotoVoltaic unit (fictive, under Hypersim),
- SC : SuperCapacitor (real, 4 modules of supercapacitors in series),
- CH : Local loads composed of 6kW fictive critical loads and of 1.2 kW real non-critical loads,
- CH On/Off is the switching signal for the 1.2 kW non-critical loads.

We have performed four different tests consecutively in order to make comparisons and validate the implementation of strategies by the MCC.

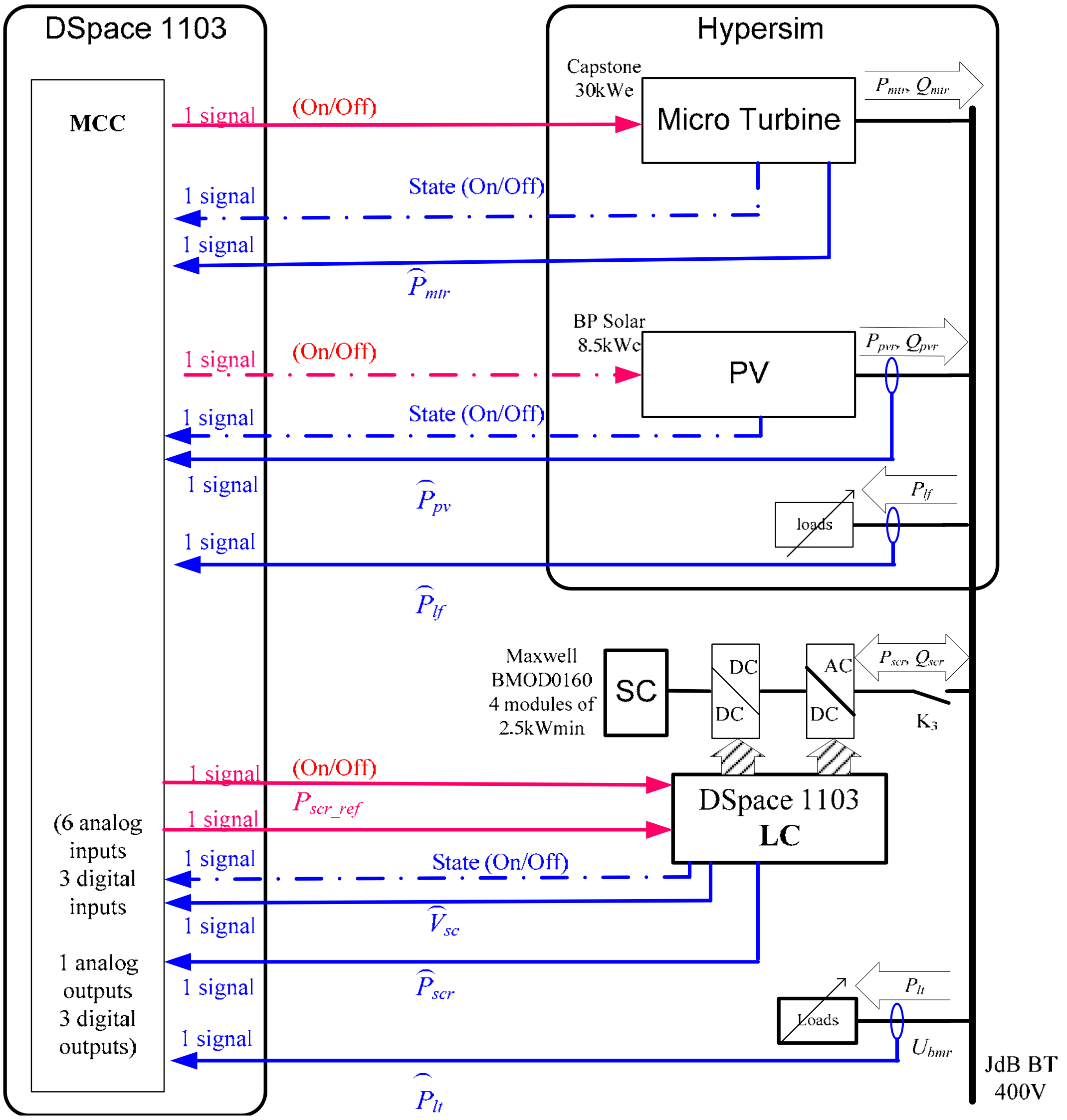


Figure VII-9. Signal communications

VII.4.3. Test of the micro turbine unit (“Zone1: MT”)

The objective is to provide a basement for comparisons. During this test, the micro turbine generator and the passive loads are connected to the microgrid. The test begins at the time t_0 with the micro turbine and 6kW critical loads. At time t_1, we connect the 1.2kW non-critical loads and at time t_2 we disconnect it.

The total load power (power of critical loads and non-critical loads) is shown at the Figure VII-10.a. When the test begins at t_0, only the 6kW critical loads are connected to the micro grid. Between interval t_1-t_2, a load step is created by the connection and the disconnection of the 1.2 kW non-critical loads.

In the Zone1 of the Figure VII-10.b, the real power, which is generated by the micro turbine is clearly shown. Since the micro turbine is the only power generation unit, its power is totally matched with the load power. The shaft speed and the gas mass flow rate of the micro turbine are visualized at the Figure VII-10.c and the Figure VII-10.d. We can notice that during the load transient, the shaft speed and the injection of the gas must vary very fast in order to follow the power production. This is not a benefit for the micro turbine.

The DC bus terminal voltage (Figure VII-10.e) of the micro turbine and its re-zoomed view (Figure VII-10.f) are also recorded. This voltage is well controlled during the test. Two peaks appear at time t_1 and t_2, because of the sudden load transients.

VII.4.4. Impact of the PV unit (“Zone2: MT+PV”)

The PV unit is connected to the microgrid at the time t_3, in order to study the influence of the renewable energy generation. The PV unit generates an intermittent power (Figure VII-10.g) at the time t_3. 1.2 kW loads step is performed between times t_4 and t_5 (Figure VII-10.a). The micro turbine (Figure VII-10.b) compensates the power difference between the PV generation and the load consumption. Even if the load consumption is constant during a certain interval, the micro turbine generation varies because of the intermittent power generation of PV.

VII.4.5. Contribution of supercapacitors (“Zone3: MT+PV+SC”)

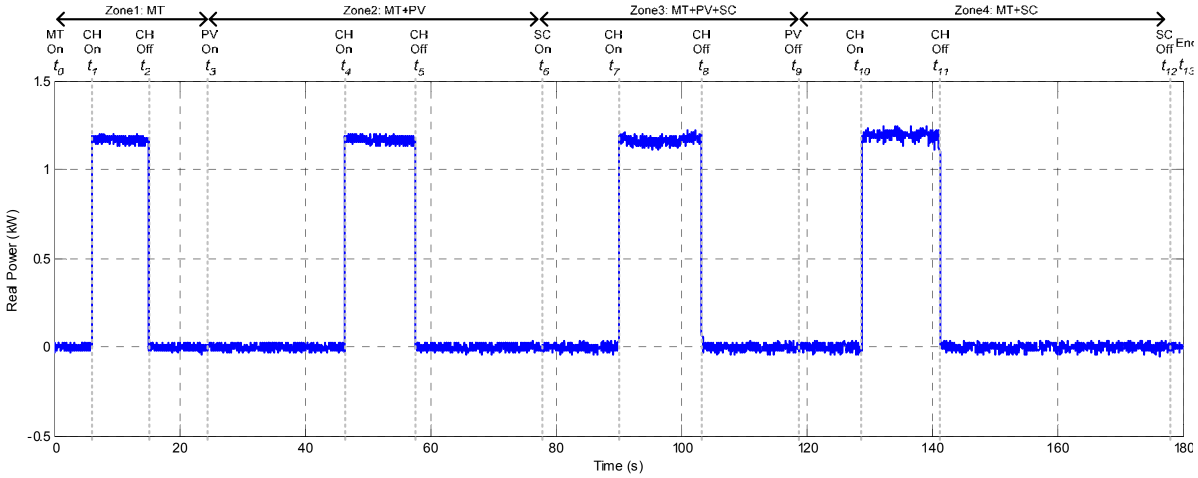
The objective of this test unit is to demonstrate the contribution of the supercapacitor unit. The SC unit is connected to the microgrid at time t_6 (Figure VII-10.h, ‘0’ represents ‘Off’ state, ‘1’ for ‘On’). 1.2 kW loads step is performed between times t_7 and t_8 (Figure VII-10.a). The PV unit continues to generate the intermittent power (Figure VII-10.g). In this case, the supercapacitor unit manages the power very quickly (Figure VII-10.i). The more power is exchanged with the supercapacitor, the more noise from the power electronics is injected to the microgrid. This noise influences a little bite the balance of the DC bus voltage of the micro turbine (Figure VII-10.f). But the peaks due to the load transient are now smaller (t_7 and t_8 of the Figure VII-10.e) than without the supercapacitor unit (t_1, t_2, t_4 and t_5 of the Figure VII-10.e). The supercapacitor terminal voltage is recorded at the Figure VII-10.j. It varies according to the exchanged power with the microgrid. The micro turbine power generation is better stabilized (Zone3 of the Figure VII-10.b) than without supercapacitor unit (Zone1 and Zone2). Therefore, the shaft speed (Figure VII-10.c) and the gas mass flow rate (Figure VII-10.d) of the micro turbine are also stabilized thanks to the contribution of the supercapacitor unit.

VII.4.6. Operating during the night (“Zone4: MT+SC”)

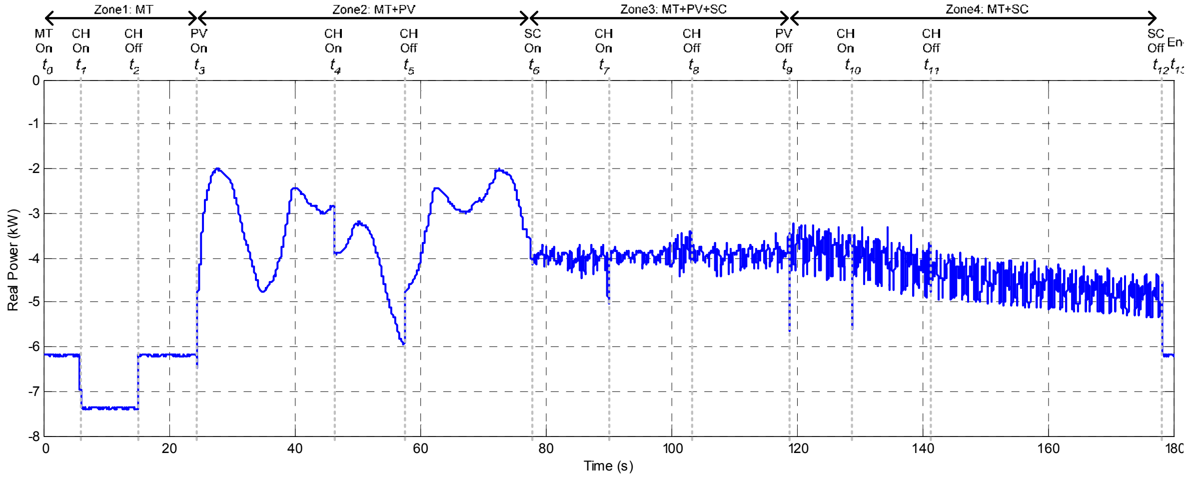
The PV unit is disconnected from the microgrid at the time t_9 (Figure VII-10.g); the moment when it was generating about 4 kW. The only disturbance to the microgrid is the local loads. Therefore, this test can highlight the performance of the micro turbine, which manages to control the power in a long-time range. 1.2 kW loads step is performed between times t_{10} and t_{11};

After the disconnection of the PV unit at time t_9, the supercapacitor unit compensates this 4kW power variation immediately (t_9 at the Figure VII-10.i). Therefore, a little more noise is injected to the microgrid (interval t_9-t_{12} at the Figure VII-10.i) and influences the micro turbine real power at the microgrid connection point (interval t_9-t_{12} at the Figure VII-10.b). The supercapacitor terminal voltage (Figure VII-10.j) decreases rapidly owning to its approximate 2kW power generation. The micro turbine power generation remains stabilized (Zone 4 of the Figure VII-10.b) and also during variations of local loads (time t_{10} and t_{11} Figure VII-10.a). Also through this test, we can notice the performance of the micro turbine, which controls the power in a long-time range (interval t_9-t_{12}). The shaft speed (Figure VII-10.c) and the gas mass flow rate (Figure VII-10.d) are always stabilized with the contribution of the supercapacitor unit.

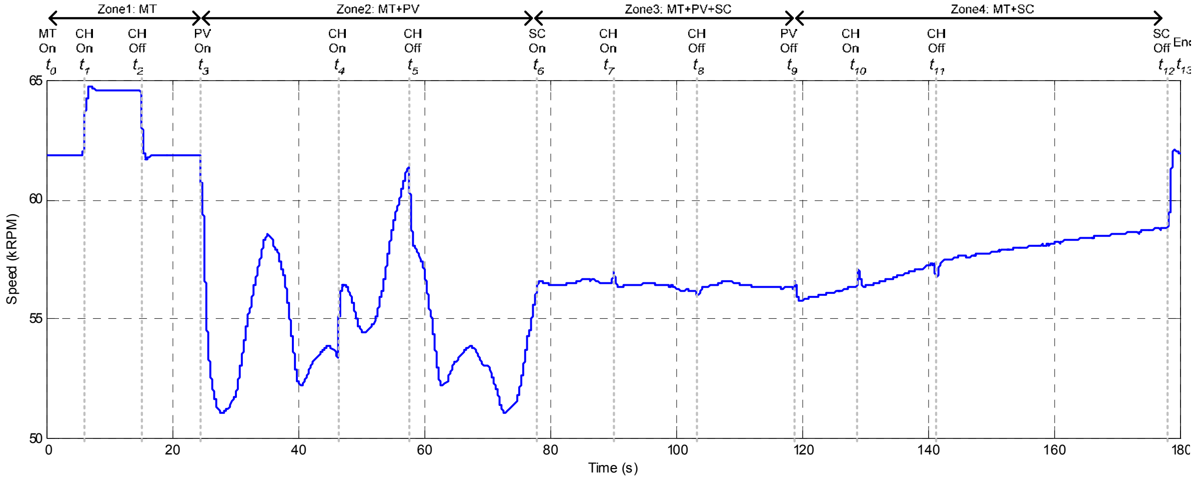
Between t_{12} and t_{13}, the supercapacitor unit is unloaded (Figure VII-10.j), we notice that the real power of the micro turbine unit is increased (Figure VII-10.b).



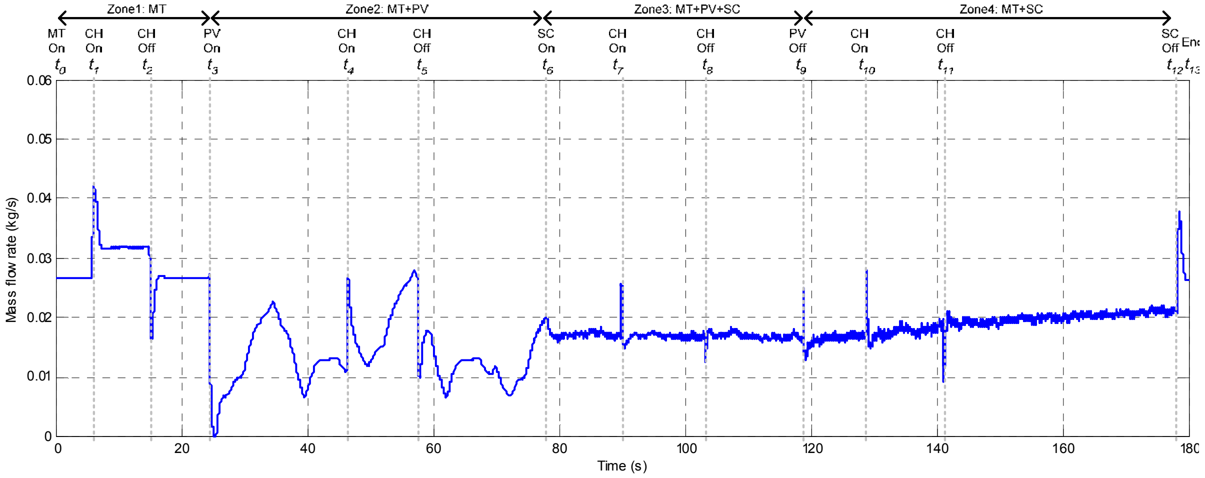
(a) Microgrid non-critical loads (by the real device)



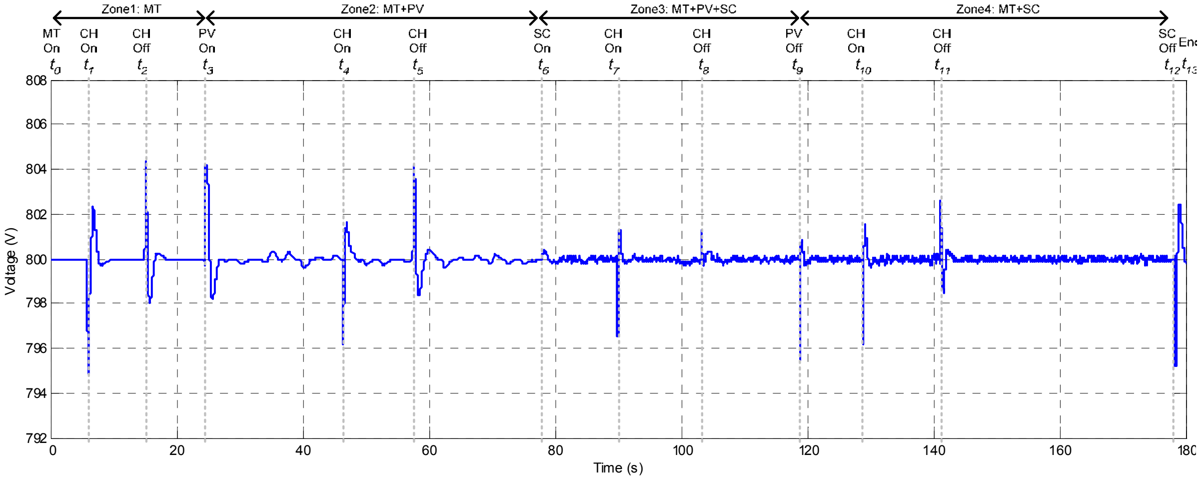
(b) Power from the micro turbine unit (by HIL)



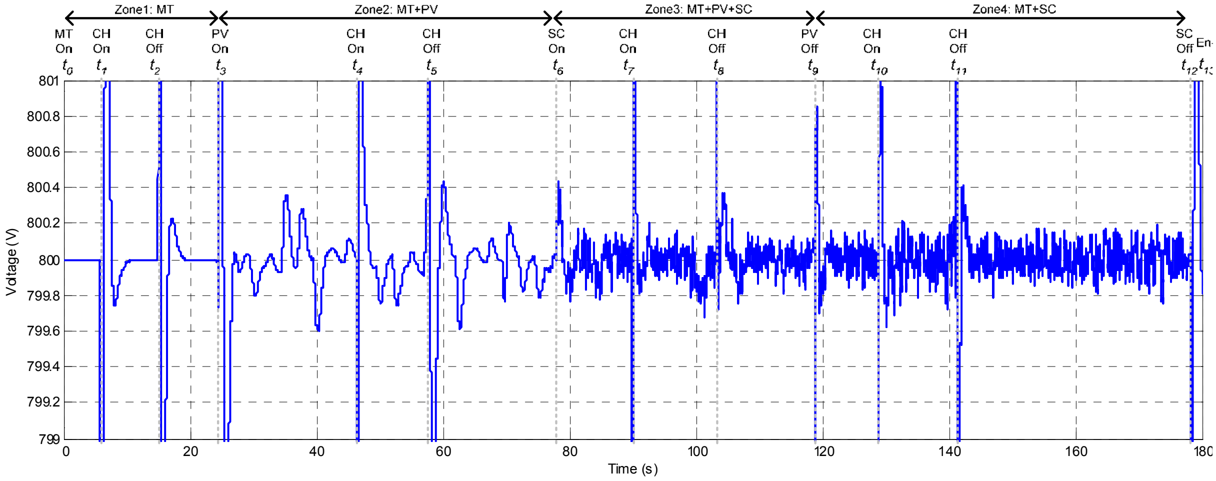
(c) Shaft speed of the micro turbine (by HIL)



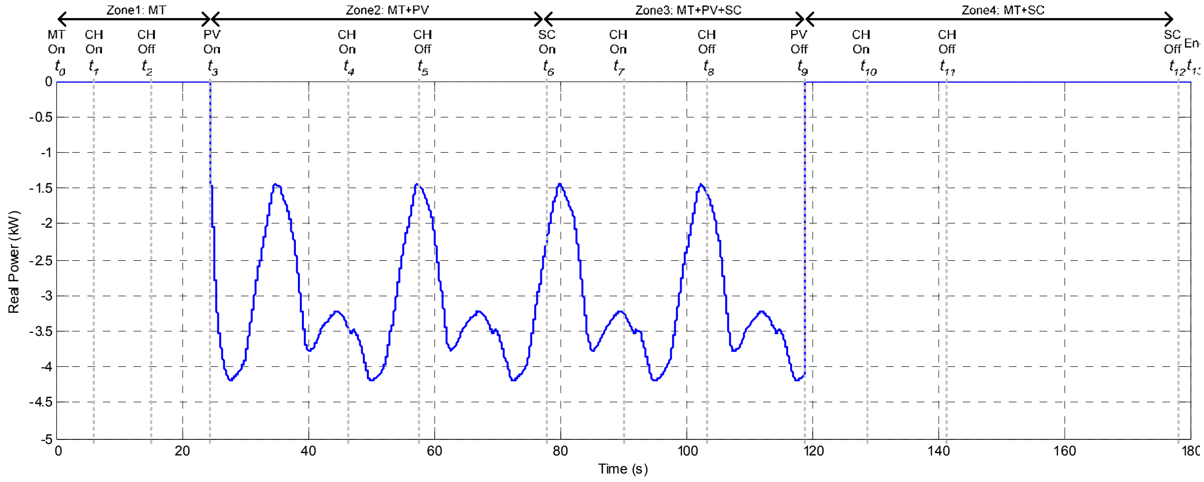
(d) Gas mass flow rate of the micro turbine (by HIL)



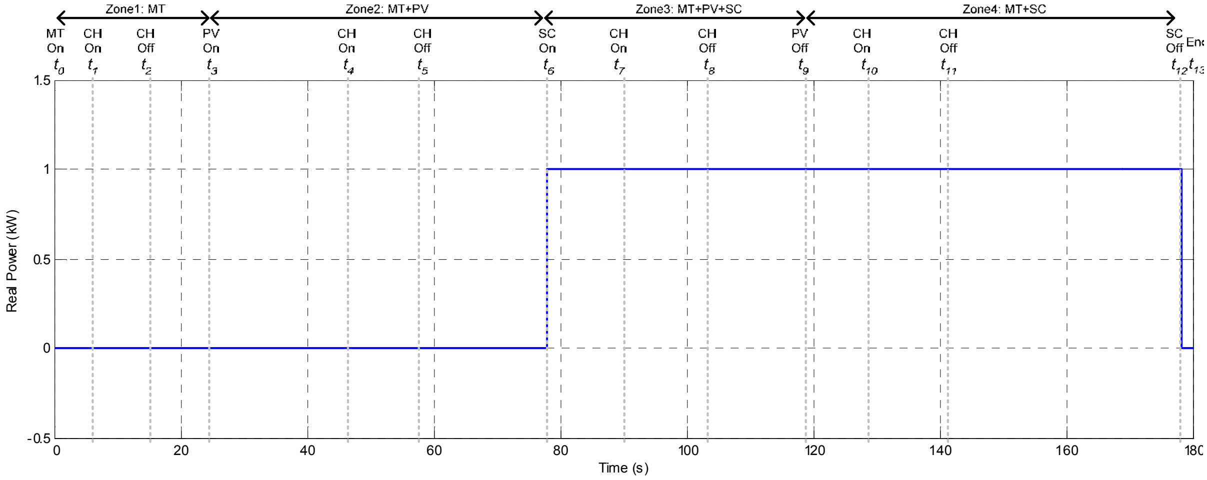
(e) DC bus terminal voltage of the micro turbine (by HIL)



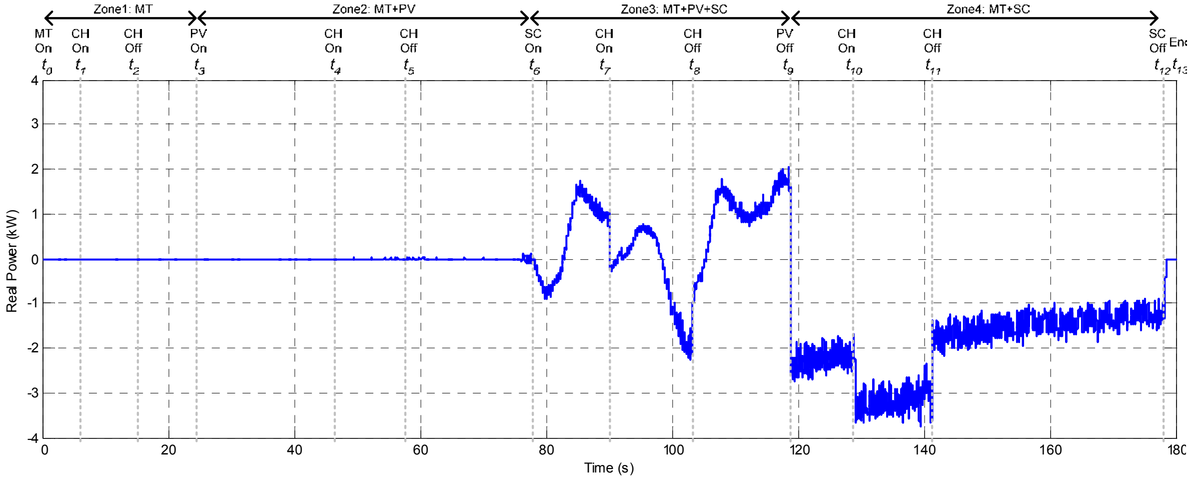
(f) Re-zoomed DC bus terminal voltage of the micro turbine (by HIL)



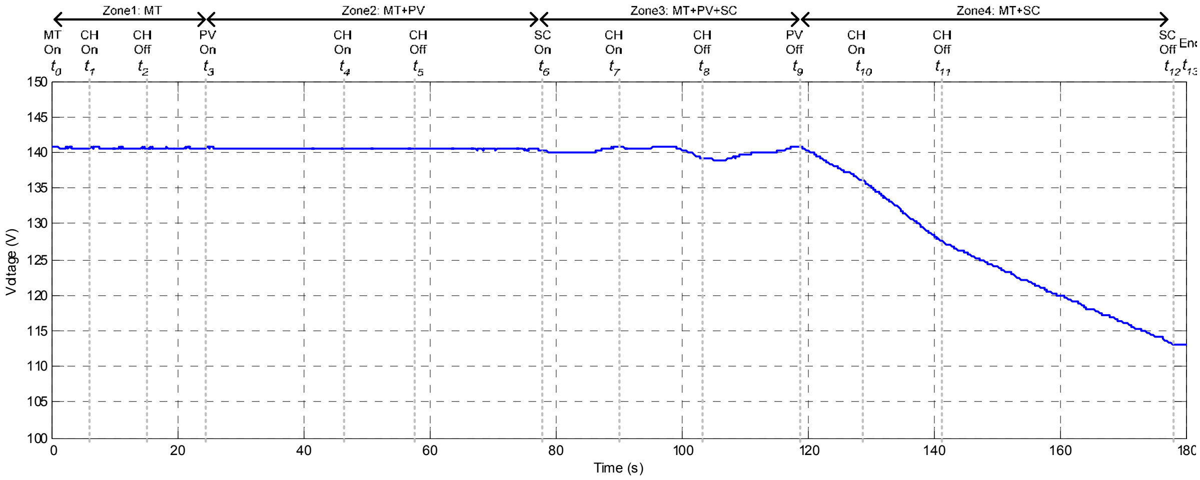
(g) Power from the photovoltaic unit (by HIL)



(h) On/Off state of the supercapacitor unit (by the real device)



(i) Exchanged power of the supercapacitor unit (by the real device)



(j) Supercapacitor terminal voltage (by the real device)

Figure VII-10. Obtained HIL test results

VII.5. Conclusion

In this chapter, we have presented the MCC for the islanded mode of the microgrid.

The microgrid modeling has been firstly presented. This modeling takes into considerations the specific limits of each DG unit, including type of the DG unit, sort of generation, time-dependency of the prime source, maintenance interval and environmental impacts. Afterwards, the MCC design is detailed by using the inversion of the power flow modeling. The protection and the regulation of the storage level for the supercapacitor unit are also implemented.

Some tests are performed to validate the MCC design, which is proposed in this research work. The test results justify the proposed MCC design for the contribution of the supercapacitor unit. If the microgrid operates without the supercapacitor unit, the turbine must compensate all power fluctuations within the microgrid. The fluctuations can be either the load variations either the intermittent power generated by the renewable energy generators, even if a transient load step occurs. The shaft speed and the gas injection are fluctuating very fast. It is not a benefit of the micro turbine. With the association of the supercapacitor unit, the operating of the micro turbine is improved since power variations have been decreased.

The HIL test results notice that the micro turbine operating is stable and manage the power with show dynamic. The supercapacitor unit manages well the microgrid power in a short-time range, even if a load step occurs. The results of tests validate our MCC design.

Conclusion générale et perspectives

Les contributions de ces travaux de cette thèse concernent deux aspects.

En premier lieu, cette thèse propose un formalisme permettant la « Représentation Multi-Niveaux » du modèle d'un système de production électrique facilitant la conception de sa commande et la supervision locale des transits de puissance en son sein. Nous avons appliqué ce formalisme à trois systèmes différents : un système de production basée sur une micro turbine à gaz, un système de production électrique basé sur des panneaux photovoltaïques et un système de stockage basé sur des supercondensateurs. Les résultats de simulation et expérimentaux ont montré la pertinence et l'intérêt de ce formalisme original.

En second lieu, cette thèse propose une organisation possible du système électrique d'un micro-réseau reposant sur une supervision centrale. En utilisant la modélisation d'un micro-réseau et du réseau de distribution, la supervision centrale est conçue sur l'inversion de différents modèles établis pour différentes échelles de temps pour permettre la gestion énergétique sur le long terme et l'équilibre des puissances en temps réel. Des essais Hardware-In-the-Loop (HIL) ont été effectués pour valider cette méthodologie de conception de la supervision centrale.

Dans la première partie de la thèse, les formalismes existants sont tout d'abord analysés. En analysant deux systèmes de production, la micro turbine et les panneaux photovoltaïques, les avantages et les limites des différents outils pour la modélisation et la conception des commandes ont été illustrés. Le Bond Graph nous permet de modéliser un système, mais il ne nous donne pas de méthode pour la conception de la commande. Le Graphe Informationnel Causal est pratique pour décrire l'ordonnancement des équations mathématiques entre variables physiques, mais son utilisation pour un système complexe sera lourde. La Représentation Energétique Macroscopique nous permet de construire une description synthétique d'un système complexe et nous permet de concevoir l'organisation de la commande des grandeurs dynamiques rapides. Par contre, elle ne nous permet pas de superviser les puissances au sein d'un système de production ou de stockage.

Pour répondre à notre objectif de conception de la gestion d'un réseau électrique, nous avons proposé un nouveau formalisme : la 'Représentation Multi-Niveaux'. Ce dernier est une extension de la REM qui fait apparaître des informations supplémentaires, comme l'interface permettant le calcul des puissances et la modélisation des flux de puissance entre les différents éléments constituant le système de production électrique. En fixant une chaîne d'action selon des objectifs définis, la structure du dispositif de commande est obtenue de façon systématique par l'inversion de ce modèle graphique et repose sur une hiérarchisation des fonctions du dispositif de commande. Cette organisation modulaire et hiérarchique du système de commande est organisée en quatre niveaux correspondant aux techniques de contrôle des convertisseurs électroniques de puissance, aux algorithmes de commande (de l'Automatique) et à la supervision des flux de puissance qui fixe les puissances actives et réactives. Cette organisation générique du dispositif de commande apporte une modularité et une compatibilité vis-à-vis de différentes technologies de générateurs. Ainsi, nous avons appliqué cette proposition de formalisme à trois types de productions décentralisées. Il s'agit d'une source de production programmable (une micro turbine à gaz), une source non-programmable (une centrale photovoltaïque) et un dispositif de stockage (des supercondensateurs). Ces trois sources sont représentatives de celles utilisées dans un micro-réseau.

Pour la micro turbine à gaz, la construction de sa modélisation et de sa commande s'est faite étape par étape à l'aide de la RMN. Pour le mode en connexion avec un réseau de distribution, la micro turbine génère la puissance en régime transitoire avec un temps de réponse lent compatible avec la dynamique des générateurs externes. Pour le mode en îlotage, la micro turbine contrôle les tensions du micro-réseau avec un temps de réponse rapide. Une cohérence a été constatée entre les résultats de simulation et expérimentaux. Sur cette base, les résultats de simulation valident notre modélisation et notre structure de commande.

La structure de conversion électronique du système de production basé sur des panneaux photovoltaïques et celle du système de stockage à base de supercondensateurs sont similaires. L'intérêt de la RMN est de montrer que la conception de la commande peut être très différente pour des structures électroniques de conversion similaires. Des vérifications et comparaisons entre la simulation et l'expérimentation ont été effectuées pour valider la RMN.

Dans la deuxième partie de ce rapport, nous avons abordé l'étude du système électrique d'un micro-réseau. Les générateurs traditionnels ne sont pas utilisés dans ce micro-réseau étudié. Les trois systèmes de production et de stockage précédemment étudiés sont utilisés au sein du micro-réseau étudié. Leur utilisation a été respectivement spécifiée. La micro turbine garantit la fourniture en énergie. Les panneaux PV produisent une puissance aléatoire. Les supercondensateurs sont utilisés pour générer de la puissance en régime transitoire. La distance entre ces dispositifs est courte et une supervision centrale basée sur un bus de communication avec les générateurs a été choisi.

La supervision centrale pour le mode connecté à un réseau de distribution est conçue par l'inversion de la modélisation du micro-réseau. Le contrôle a été détaillé pour une participation aux services systèmes en utilisant une caractéristique « fréquence-puissance active ». En utilisant ce contrôle, le micro-réseau peut participer à la régulation primaire de la fréquence. Nous avons présenté également l'implantation d'une régulation secondaire de la fréquence qui est envoyée par le gestionnaire du réseau de distribution. La protection et la régulation du niveau de stockage des supercondensateurs sont prises en compte. Des résultats de simulation valident la faisabilité de cette supervision centrale.

La supervision centrale pour le mode en îlotage a été conçue par inversion de la modélisation. La protection et la régulation du niveau de stockage des supercondensateurs sont également ajoutées pour une optimisation de leur utilisation. Des résultats des essais HIL mettent en évidence l'avantage de l'association des supercondensateurs au sein du micro-réseau en utilisant la supervision centrale proposée. La micro turbine contrôle bien les tensions du micro-réseau et génère la puissance en régime permanent. Les supercondensateurs génèrent la puissance en régime transitoire pour compenser les fluctuations de puissance. Ces fluctuations peuvent avoir comme origine la centrale photovoltaïque et/ou les charges.

Les travaux de cette thèse ont initié la recherche sur les micro-réseaux au sein de notre laboratoire. D'autres activités de recherche ont commencé dans le périmètre des travaux de cette thèse.

- Au niveau de la supervision locale

Dans cette thèse, les différentes sources étudiées sont connectées en alternatif (AC). Un couplage sur un bus continu commun de l'ensemble des sources est aussi envisageable pour former un générateur actif hybride. Avec ce type de couplage intégrant des sources d'énergie renouvelable et de stockage, deux types de générateurs sont actuellement à l'étude. Le doctorant Di LU travaille sur l'association d'un générateur photovoltaïque, d'une batterie et de supercondensateurs. L'intégration et la coordination d'un générateur éolien, d'une pile combustible, d'un électrolyseur et de supercondensateurs font l'objet de la thèse de Tao ZHOU. Dans ce contexte, la Représentation Multi-Niveaux est également appliquée à la modélisation et à la conception de la commande pour ces générateurs actifs hybrides couplés sur un bus continu commun.

Des phénomènes transitoires font l'objet d'importants travaux de recherche (la thèse de Fouad SALHA), comme le démarrage et l'arrêt d'un générateur, la commutation entre deux modes de fonctionnement de la micro-turbine, le comportement d'un micro-réseau au moment d'un creux de tension etc. Elles nécessitent également de la recherche sur la protection des dispositifs.

- Au niveau de la supervision centrale

Une association possible de nombreux systèmes de production et de stockage permet d'avoir de nombreuses possibilités de gestion pour une optimisation économique du fonctionnement d'un micro-réseau. Ce domaine de recherche est mené par une thèse de Firas ALKHALIL financée par le gouvernement syrien.

En ajoutant de nombreux systèmes de production dans un micro-réseau, la communication des signaux sera alourdie. Un bus de communication ne sera plus raisonnable. Une supervision centrale avec un logiciel de supervision PcVue est en train d'être développée par un ingénieur de recherche Frédéric COLAS. Elle nous permet de communiquer des signaux par un réseau informatique. La première application sera réalisée à partir de l'essai HIL réalisée dans le chapitre 7, en remplaçant tous les liaisons électriques pour la communication par PcVue.

Un post-doctorant Hicham FAKHAM travaille sur l'utilisation des multi-agents pour la supervision du micro-réseau. En utilisant la supervision centrale par PcVue et en associant de nombreux systèmes de production, une supervision décentralisée serait intéressante pour effectuer une comparaison avec la supervision centralisée.

D'autres perspectives sont aussi envisageables pour notre micro-réseau étudié :

- Les supervisions locales pourraient être implantées sur une micro turbine réelle et ainsi que sur une centrale basée sur les panneaux photovoltaïques.
- Les deux fonctionnements en régime permanent (mode de connexion et mode d'îlotage) ont déjà été discutés dans cette thèse. Les fonctionnements transitoires dus à la commutation entre ces deux modes sont également très intéressants pour la recherche, par exemple, pour réduire le courant transitoire pendant la commutation.

La poursuite de ces perspectives permettrait d'imaginer le système électrique d'un micro-réseau parfaitement bien adapté à l'accueil des nouveaux modes de production à base d'énergies renouvelables.

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RESUME

Un micro-réseau est un exemple prometteur d’évolution d’architecture de réseau qui consiste à regrouper les différents producteurs et consommateurs autour d'un réseau moyenne tension. Ce système hybride multi-source est donc composé d'au moins une unité de production décentralisée conventionnelle et éventuellement d'une unité de stockage et d’une unité de production basée sur des énergies renouvelable. L’utilisation de cette structure permet de réaliser une minimisation immédiate des pertes liées au transport de l’énergie, une fiabilité accrue de la fourniture et une possibilité de fournir une énergie d’une haute qualité. Dans ce mémoire, nous étudions un micro réseau reposant sur l’utilisation d’une turbine à gaz, d’une centrale photovoltaïque et d’une unité de stockage à base de supercondensateurs. Toutes ces sources sont couplées au micro réseau par des convertisseurs électroniques de puissance et sont interconnectées au gestionnaire central du micro-réseau. Des supervisions locales et une supervision centrale sont utilisées pour ce micro-réseau étudié afin de réaliser une optimisation de son fonctionnement. Par conséquence, la première partie de ce mémoire est consacrée à la formalisation d’une méthode permettant la conception systématique des supervisions locales et des dispositifs de commande des unités de production et de stockage. La seconde partie de cette thèse est consacrée à la gestion proprement dite de l’ensemble de ces moyens de production et de stockage en vue d’optimiser les services fournis aux micro-réseaux. Des résultats de la simulation et de l’expérimentation valident notre conception de la supervision du micro-réseau.

Mots clefs:
Micro-réseau, micro turbine, panneau photovoltaïque, supercondensateur, supervision locale, supervision centrale, modélisation, conception de la commande, simulation.

ABSTRACT

A microgrid is a promising future network architecture which is coupling the various generators and consumers in a distribution network. This hybrid multi-source system is composed of at least one conventional generation unit and possibly a storage unit and/or a production unit based on renewable energies. Using this structure allows an immediate minimization of the losses by the energy transport, a greater reliability of power delivery and an ability to provide a high power quality energy. In this paper, we study a microgrid based on the use of a micro gas turbine, a photovoltaic array and supercapacitors. All these sources are coupled to microgrid by power electronic converters and are interconnected to a microgrid central controller. Some local controllers and the microgrid central controller are used for the studied microgrid to achieve its operation optimization. Therefore, the first part of this thesis is devoted to establish a formalism method for a systematic design of local controllers. The second part of this thesis is devoted to the management of all these production and storage units, in order to optimize the microgrid operating. Simulation and testing results validate our design of the microgrid controllers.

Keywords:
Microgrid, micro turbine, photovoltaic array, supercapacitor, local controller, microgrid central controller, modeling, control design, simulation.