Dynamic Power Flow Control for a Smart Micro-grid by a Power Electronic Transformer

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Dedication

To my husband, Nitin Mathur

Abstract

A novel strategy, for control of the power flow for a smart micro-grid is proposed. The utility grid power is dynamically controlled by a **P**ower **E**lectronic **T**ransformer (PET). A 60 Hz, step-down transformer is generally used at the point of common coupling (PCC), to connect the micro-grid to the power system grid. Substitution of the conventional 60Hz transformer, by a PET, results in enhanced micro-grid power management system, during grid-connected operation. The smart micro-grid is a set of controllable loads and distributed energy resources (DER); both renewable and non-renewable; that supply demand of a group of customers. The proposed dynamic power limiter (also referred to as PET) is a high-frequency, isolated power-converter system, comprised of a high-frequency step-down transformer and three-phase to single-phase matrix converters. The matrix converters are modulated with a novel pulse width modulation (PWM) strategy for a bi-directional power flow control. The output of the matrix converter generates a high frequency (few kHz) pulsating single phase AC at the primary and secondary of the transformer, which are phase shifted for active power control. The PET also allows voltage regulation by control of reactive power. The entire system; represented as two, three-phase AC systems with an intermediate high-frequency transformer; is simulated using Matlab/Simulink. The equivalent system has utility grid at the input side and a micro-grid on the output side. The micro-grid is modeled as an interconnected system consisting of set of DERs and smart loads. The simulation analyzes the change in micro-

grid's power generation and consumption in response to the change in its local grid frequency, upon limiting the utility grid power. The PET hence restores the system frequency by adjusting supply and demand at the PCC. The micro-grid can now participate in frequency regulation for the main grid. The simulation results are obtained to verify the operation and claims of the dynamic power limiter as stated below:

1. Restricted active power flow to the micro-grid, at a desired value determined by the main utility grid.
2. Utilization of the change in local grid frequency, to dynamically control the active power generation or consumption within the micro-grid.
3. Decentralized control of the DERs as well as the controllable loads, which operate synchronously, to supply the demand within the micro-grid.
4. Bi-directional active-power flow capability at the PCC.
5. Voltage regulation by control of reactive power.
6. Contribution of the micro-grid components in frequency regulation of the main grid.
7. Smooth transition from islanding to grid-connected mode of the micro-grid, without the need of grid synchronization.
8. Extra degree of freedom due to the presence of active-power controller in a possible deregulation and market strategy within the micro-grid.

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List of Acronyms

AGC	Automatic generation control
CERTS	Consortium for electric reliability technology solution
CHP	Combined heat and power
DER	Distributed energy resources
DG	Distributed generator
DS	Distributed storage devices
LFC	Load frequency control
LV	Low voltage
MV	Medium voltage
NEDO	New energy and industrial technology development organization
PCC	Point of common coupling
PET	Power electronic transformer
PHEV	Plug-in hybrid electric vehicle
PWM	Pulse width modulation
RPS	Renewable portfolio standard
SCC	Standards coordinating committee

Chapter 1

Introduction

1.1 Overview

Sophisticated and smart technologies in today's consumer products make it essential to promote modernization for the current electric power generation and distribution. The varying customer necessities, new generation appliances and complex operating strategies challenge the security and quality of the power supply. With increasing complexity in the power grid, a new infrastructure that better handles these changes, in interest of the society, economics as well as environment is essential. In a typical power system as shown in figure 1-1, the transmission and distribution system delivers electricity from the generating site to residential, commercial, and industrial facilities. A typical electric power distribution network [1], includes medium-voltage power lines, substations, transformers, low-voltage distribution wiring (<1kV) and meters. The distribution substation transformers provide electricity at appropriate voltage levels to its consumers. The components of the electric power grid have advanced in technology with growing need of the customers, thus leading to a more resilient and reliable network.

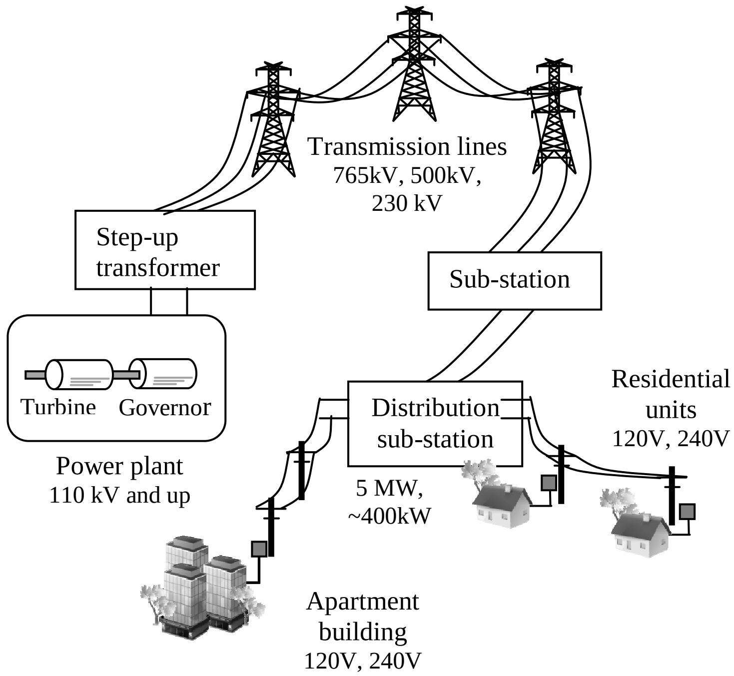

Figure 1-1 Typical power system diagram

Small scale electricity generation (typically in the range of 3 kW and 10,000 kW) also termed as distributed generation (DG) technology [2]-[4], is considered to be the solution to the technical and economical issues that may emerge upon modernization of the power system network. DG technologies [4] include solar generators, wind turbines, microturbines etc. The DG technology effectively integrates the renewable resources in the existing power grid. The renewable portfolio standards (RPS) [5], aims about 2-25% of renewable power generation participation. With increase in research activities involving DG systems, the concept of micro-grid has emerged. Micro-grids are often defined as a group of DERs and associated loads, that operate interconnected with the main grid. They may also island and operate autonomously [6]-[13]. Micro-grids have found applications in automobile industry, utility, appliances, military, aerospace etc.

The power distribution system operates between 120 Volts and 38 kV. Distribution transformers [14], [15] are the prime components of a power distribution system. Their role is mainly to reduce the primary voltage of electric distribution system to the utilization voltage serving the customer while maintaining the frequency during the transformation. Most commercial and industrial buildings require several low-voltage transformers to decrease the voltage of electricity received from the utility to the levels used to power lights, computers, and other electric-operated equipment. Distribution transformer designs vary with the needs of the end-user or a particular utility (cost of energy, capacity, etc.). Line frequency transformers (50Hz/60Hz) are often heavy and bulky. Since the transformer size is inversely proportional to the frequency and saturation flux density, high-frequency operation of the magnetic core has weight and size reduction advantages. Modern power grid is getting complex and widespread. The current power system needs to keep up with these new technologies and be more reliable, efficient and consumer friendly. It also needs to consider integrating improvised communication infrastructure as well as energy efficient appliances.

1.2 Scope of thesis

A conventional power system transmission and distribution network, consisting of a 60-Hz distribution transformer, is shown in the one line diagram [1] in figure 1-2. The power system grid supplies active power to the load demand of the system. Here the power is made available to the load by the utility as per the demand and the power flow is determined by the supply-to-demand balance.

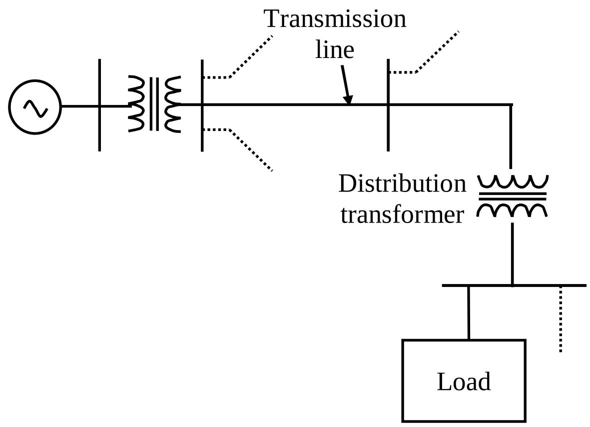

Figure 1-2 Simplified one line diagram of transmission and distribution system [1]

In some areas of public grid, with high penetration of DERs, these areas operate as a micro-grid. From the point of view of the grid operator, a connected micro-grid can be controlled as if it was one entity. In [16] micro-grid is defined as "*the portion of an electric power distribution system, which is located downstream of the distribution substation and it includes variety of DERs and different types of end users of electricity*". Similar to the main power system, micro-grid can generate, distribute and regulate the flow of electricity to consumers. Figure 1-3 describes the typical structure of a micro-grid and its components. As shown, a micro-grid comprises of the low voltage (LV) side of a distribution transformer. It serves variety of customers, e.g. residential, commercial and industrial buildings. It may consist of several basic technologies for operation which include DERs, interconnection switches and control systems. Wind turbines, photovoltaic (PV) arrays, flywheels, battery storages etc. are expected to contribute significantly as microsources in a micro-grid. The electrical connection point of the micro-grid to the utility system is the point of common coupling (PCC). The micro-grid normally operates in a grid-connected mode through a 60 Hz transformer at the PCC. It is more or less decoupled from the main power grid as and when required, but needs to be well planned to avoid causing problems. However, it is also expected to provide sufficient generation capacity, controls and operational strategies to supply at least portion of the load, after being disconnected from the distribution system and remain operational as an autonomous (islanded) entity.

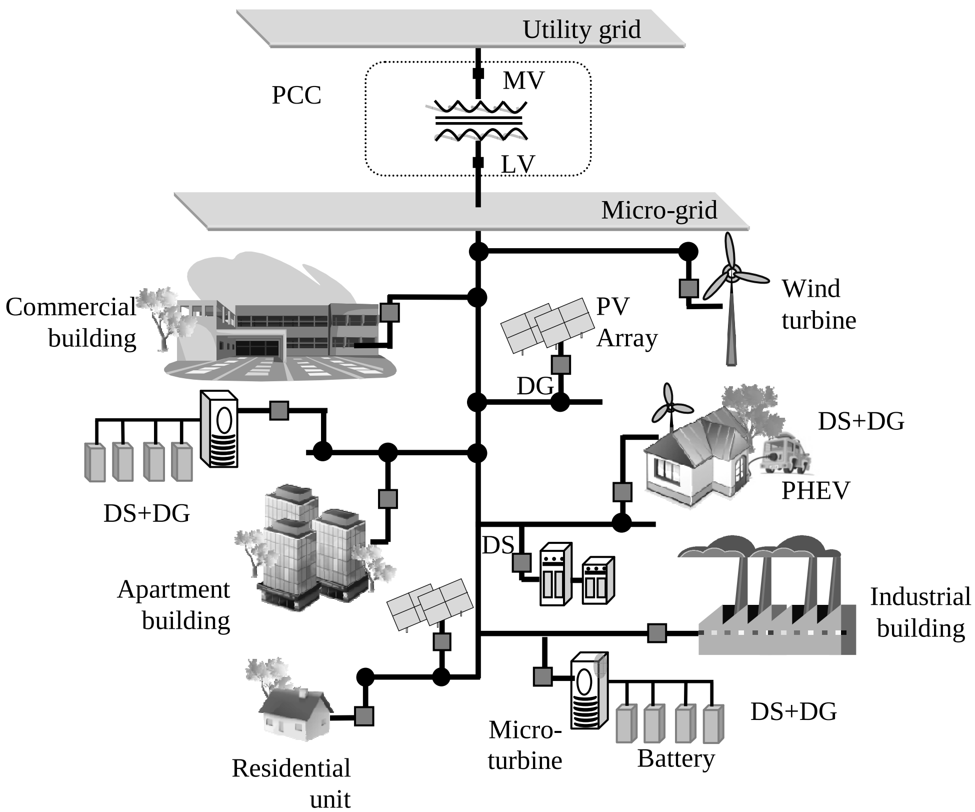

Figure 1-3 Typical micro-grid structure

While connected to the grid, the microsources contribute to the majority of the demand within the micro-grid and the difference in supply and demand is made available from the utility. The distribution transformer at the PCC thus supplies with the required power flow as determined by the load demand of such a micro-grid. Current micro-grid operation solutions rely on complex communication and control systems as well as extensive site engineering. The thesis scopes a study to find optimal simplified solutions and a decentralized control of the micro-grid components by a PET.

1.3 Proposed topology

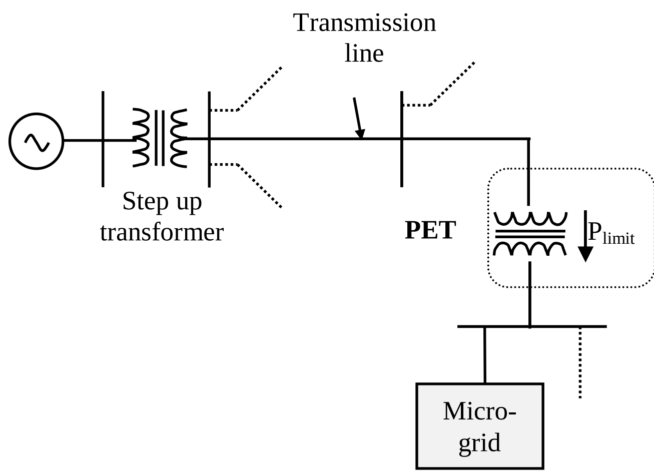

Figure 1-4 Proposed topology

In the proposed technology, the conventional 60 Hz distribution transformer is substituted by a dynamic power limiter at the PCC, shown in figure 1-4. A power electronic transformer [17]-[20] is a high-frequency isolated power converter system comprised of a high-frequency step-down transformer and three-phase to single-phase matrix converters [21]-[23] as shown in figure 1-5. The matrix converters are modulated with a simple triangle comparison based novel PWM strategy [23] that results in high frequency single phase AC at the transformer primary and secondary. The switching frequency of the PET ranges as high as 10-20 kHz, which also adds the size and weight advantages over the conventional line frequency transformer. This is applied at distribution voltage levels (here, 20kV to 0.4kV distribution line). The over-all simplified system is modeled as two line frequency AC sources with high frequency AC link. The primary side AC source is that of the utility while the secondary side AC source is an equivalent source from micro-grid components. The power flow between the two AC systems is achieved with phase-shift technique similar to a dual-active bridge for a DC system [25]-[27].

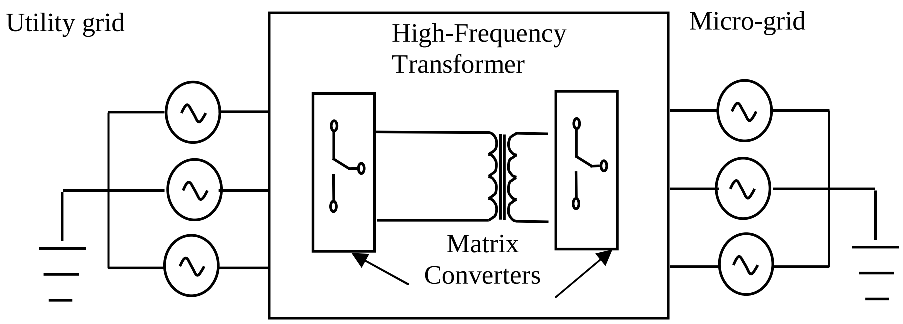

Figure 1-5 Simplified representation: Two AC systems with PET

By introducing a PET, the active power flow from the grid can be controlled at the PCC to a desired value determined by the utility. Also dynamic bi-directional power flow control can be achieved. Due to presence of the PET, the grid frequencies of the two three phase AC systems at either side of the PET can be different. Thus smooth transition from islanded mode to grid connected mode can be achieved without grid-frequency synchronization. This is another advantage of the PET. The capability of power flow control from the power system grid also offers an extra degree of freedom which can be used to improve the market strategy and deregulation inside the micro-grid [6].

In the grid-connected mode of a micro-grid, the DGs are controlled to supply a pre-set value of active power. To maintain power balance within the micro-grid, the power system grid supplies the difference of supply (active power generated by DGs) and demand (load active power) [6], [9]. In the event of a sudden load change in the micro-grid, the active power flow at the PCC can vary significantly which may be undesirable during the peak load demand from the power system grid. Hence when the active power at the PCC increases beyond a pre-set limit, the PET restricts the active power flow from the power system grid and thus resulting in decrease in the grid-frequency within the micro-grid. The grid frequency at the power system grid does not change. This information can be locally sensed by the DG units and controllable loads in the micro-grid for dynamic active power control.

The decentralized control of the micro-grid component is achieved at the PCC, with the change in grid frequency as the control parameter. The PET also allows the micro-grid components to participate in frequency regulation of the main grid. Hence it can be claimed that the renewable sources of the micro-grid could be optimally utilized. Voltage regulation is also achieved by reactive power control at the front end converter. The PET allows control over reactive power flow from the utilities due to the PWM strategy employed. Thus both voltage and frequency of the interconnected power system are maintained under any load disruptance or network structure, which ensures overall system stability. Table 1 compares the micro-grid with a smart micro-grid consisting of a PET at the PCC and lists the contribution of the thesis to achieve the claims.

Table 1 Micro-grid Vs. Smart Micro-grid

<table>
<tr><th>Micro-grid</th><th>Smart Micro-grid</th><th rowspan="3">Thesis Contribution</th></tr>
<tr><td>Distribution transformer (60Hz) at PCC</td><td>PET (10 kHz) at PCC</td></tr>
<tr><td colspan="2">Supply: DER units, Utility grid resources
Demand: Load (controllable/non-controllable)</td></tr>
<tr><td>▪ Power flow is bi-directional but is not controlled at the PCC</td><td>▪ Bi-directional power flow control at PCC</td><td>▪ Design and simulation of PET topology.</td></tr>
<tr><td>▪ Power flow determined by supply-demand difference in micro-grid</td><td>▪ Dynamic active power flow to a desired limit as set by the utilities.</td><td>▪ Design and simulation of closed loop controller for active power control</td></tr>
<tr><td>▪ Voltage control achieved by excitation control of generators or reactive power control.</td><td>▪ Voltage control achieved by PET by control of reactive power.</td><td>▪ Simulation results for reactive power control</td></tr>
<tr><td>▪ Frequency will not change enough to control generation and consumption</td><td>▪ Utilization of grid frequency as a control parameter.
▪ Decentralized control of micro-grid components</td><td>▪ System level design and analysis
▪ Study of several components of micro-grid and case study analysis</td></tr>
<tr><td>▪ Grid frequency synchronization is required.</td><td>▪ Smooth transition from islanded to grid-connected mode.</td><td>▪ Case study analysis and PET simulations</td></tr>
<tr><td>▪ May or may not participate in main grid frequency regulation.</td><td>▪ Participation in frequency regulation of the main-grid</td><td>▪ Case study analysis and system level simulations.</td></tr>
</table>

1.4 Organization

Chapter 1 establishes the thesis context. The proposed PET and its application to micro-grid are briefly outlined. The scope and contribution of the thesis is given. In chapter 2, the state-of-art for the electronic transformer and micro-grid is presented. The general structure and components of the micro-grid is explained. Current projects under the micro-grid theory are briefly outlined. To better understand the application of the PET and verify its claims, chapter 3 details the schematic and operation of the PET. The simulation results for PET are also explained to support the claims. Chapter 4 describes the power flow analysis for the micro-grid. The components of the micro-grid and associated control are explained to simulate the overall system. Chapter 5 explains the results for a case study of the application. Chapter 6 concludes the thesis enlisting the benefits of the smart micro-grid with a PET at its PCC. The comparison of a smart micro-grid as compared to a regular micro-grid is listed, as achieved in simulation results and case study from the previous chapters. The future work is discussed, where a smart micro-grid could incorporate an intelligent control and communication features.

Appendix A contains the simulation model for the PET as discussed in chapter 3. The system model discussed in chapter 4 and the case study in chapter 5 are given in Appendix B.

Note: Portion of this chapter is reproduced from my IEEE publications [24],[54-55]

Chapter 2

State of the Art

To understand the proposed topology of the power electronics transformer as applied to a micro-grid, it is essential to first establish a broad understanding of both the electronic transformers as well as micro-grids. The chapter describes the state of the art for these two concepts.

2.1 Micro-grid

The interconnected electric power system is vulnerable to grid failure often caused by unexpected natural phenomena. Ongoing research in countries like Europe, the USA, Japan and Canada investigates optimal integration of DERs in conventional power systems. The high amount of penetration of DERs and their potential to ensure reliable power supply to a specific group of consumers have increased research activity in the hence defined micro-grids. There have been several varying definitions for micro-grids. In [29]-[30] micro-grid is defined as intentional islands formed at electrical distribution system consisting of DERs and associated loads. Figure 2-1 shows schematic diagram of a micro-grid diagram as given in [29]. The various components of a micro-grid;

distributed generation, distributed storage, loads, interconnection switch etc are also shown. Micro-grids are often classified as utility micro-grids which contain parts of the utility and industrial/commercial micro-grids which only include customer facilities [28]-[30]. Reliability is one of the potential benefits achieved for customers that are part of a micro-grid. The utility also gains advantage of resolving overload problems by allowing intentional islanding for a micro-grid without having a power outage for those customers.

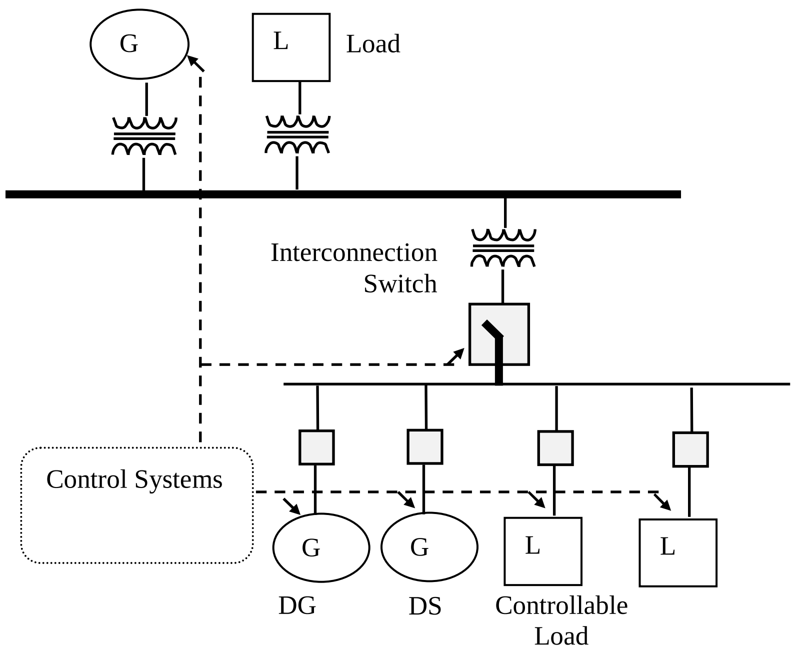

Figure 2-1 Micro-grid components

Source: Adapted from [29]

There are several micro-grid projects initiated for different applications. As part of this research, micro-grid topologies and operational configurations are being defined and a design criterion has been established. The consortium for electric reliability technology solution (CERTS) initiated the research on the impact on the power system grid reliability by DERs [31]-[33]. In Japan, the New Energy and Industrial Technology

Development Organization (NEDO) is supporting a variety of micro-grid demonstration projects [34]. The two major Canadian utilities: BC Hydro and Hydro Quebec have implemented planned micro-grid islanding application [35]-[36]. Also the European Union has supported research efforts for micro-grid projects: The micro-grids and the more micro-grids project [37]. IEEE Standards Coordinating Committee 21 (SCC) is supporting the development of *IEEE P1547.4 Draft Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power System* [38]-[40] for further development of *IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems* [40]. Table 2 [41] enlists major differences between conventional methods of distribution system planning, the developing approaches based on decentralized generation and the micro-grid approaches.

Table 2 Conventional power systems and micro-grids

PLANNING	CONVENTIONAL POWER SYSTEM	MICRO-GRIDS
Generation	• Centralized • On-site, back-up generation	• Decentralized • Med/High penetration of DER
Distribution Network	• Supplied from substation/ passive network	• Active network/ bi-directional power exchanges
Loads	• Controllable and non-controllable/Critical and non-critical	
Contingency Management	• Frequency-based load shedding • Forced power outage	• Islanding and autonomous operation • Demand response management

Source: Adapted from [41]

The micro-grid approach promises the energy delivery and supply system to be 1) Highly efficient 2) Secured 3) Reliable. Micro-grid, as defined earlier is a localized grouping of different kinds of DERs and loads that usually functions interconnected to, and synchronous with, the traditional power system distribution grid. Similar to the main power system grid, a micro-grid can generate, distribute and regulate the flow of electricity to consumers. They can be networked with one another as well as with the main grid, to increase capacity, reliability and efficiency [11]. Sometimes the cost of the existing main power grid does not affect the micro-grids. Often micro-grids are required to reliably supply all of the load demand without the benefits of a diverse set of loads and generation technologies [58]. Micro-grids are LV networks with total installed capacity of around few hundred kilowatts. They may comprise part of MV/LV distribution systems and clustered loads that are served by single or multiple DERs [41]. Based on the applications, ownerships structure and types of loads micro-grid architecture is often classified into three categories: 1) Utility micro-grid 2) Industrial/commercial micro-grid 3) Remote micro-grid. A typical structure of a micro-grid consists of several basic technologies for operation. These include, DERs, interconnection switches, and control systems [12]. The DERs include both distributed generation DGs and distributed storage devices (DS). It serves a variety of customers, e.g. residential buildings, commercial buildings and industrial parks. The electrical connection point of the micro-grid to the utility system is the point of common coupling (PCC).

A micro-grid is conceptually different than the conventional power systems. It is considered to play a potential role in resolving transmission and distribution system capacity constraints as well as satisfy customer demands of reliability and lower cost. [58]. Amongst the many key factors that affect a micro-grid operation, few are listed below:

i. Type and number of customer (residential, commercial etc.)

ii. Load characteristics

iii. Power quality constraints

iv. Type of DG technologies (dispatchable or non-dispatchable)

v. Number of DG units and their size

vi. Market participation strategies

vii. Required control and operational strategies.

Micro-grid infrastructure is rather complicated due to several variables associated. An approach to find solution to optimal configuration of micro-grid is studied in [58]. Micro-grids are expected to balance the needs of both the customer and the utility. This makes synchronization and communication between the mains grid and the micro-grid even more complicated. All the components of a micro-grid play a crucial role in power management for the system.

2.1.1 Components of micro-grid

The design, acceptance and availability of low-cost technologies, for installation and application of micro-grids, are some of the prime challenges faced and are extensively researched. Micro-grids similar to the main power grid can generate, distribute as well as effectively consume electricity. This includes several basic technologies for operation as briefly described below:

- **Distributed Energy Resources.**

DER systems are small-scale power generation technologies (typically in range of 3kW to 10,000 kW) and include both distributed generation and distributed storage units with different capacities and characteristics. The steady state and dynamic characteristics of DER units are different than those of conventional large turbine generator units. Compared to generators of centralized energy systems DG units allow a more efficient energy transmission and distribution due to local generation. DG units are small sources of energy located at or near the point of use.

The non-dispatchable nature of some of these sources poses additional power management challenges. The frequency response of these microsources [6] is based on rotating mass and is essential for very little directly connected rotating mass, like flywheel energy storage coupled through a converter. Microturbines and fuel cells have slow response to the control signals and are inertia-less. For calculating the system response to load change, the inertia of these microsources is determined by the power electronics interface associated with the DG technologies, to convert the energy into grid-compatible AC power. DG technologies typically include PV arrays, wind turbines, fuel cells, microturbines, and reciprocating internal combustion engines with generators [7]-[9]. Variable nature of some renewable energy systems rely on natural phenomenon (sunshine, wind etc.). Hence the power that can be obtained through these prime sources is difficult to predict. Also the peaks of power demand may not necessarily coincide with the generation peaks and hence storage energy systems are required. Table 2 enlists the different DER technologies and their characteristics.

Table 3 DER Technologies

DER Technology	Size-range	Source	Cost & Performance	Applications
Microturbines	25 kW – 500 kW	Natural gas, hydrogen, propane, diesel etc. fuel	20-30 % $700-$1,100/kW	Small commercial buildings e.g. motel, restaurants etc.
Combustion turbines	500 kW – 25 MW	Natural gas, liquid fuels etc.	20-45% $300-$1,000/kW	Cogeneration applications, mechanical drives,
Reciprocating Engines	5 kW – 7 MW	Natural gas, diesel, land filling gas etc.	25-45% $300-$900/kW	Widely available, backup power in commercial and industry buildings
Stirling Engines	<1 kW – 25 kW	Primarily natural gas	12-20% $2,000 - $50,000/kW	Emerging in aircraft, space, solar dish etc.
Photo-voltaic (PV) system	<1 kW – 100 kW	Sunlight	5-15% $6,000-$10000/kW	Small roof-top residential
Wind systems	Several kW – 5 MW	Wind	20-40% ~ $1000/kW	Small/large scale generation
Combined heat & power (CHP)	Several kW – 25 MW	Depends on DERs involved	50-90%	Hot water production, space heating/cooling etc.
Fuel Cells	1 kW – 10 MW	Natural gas, hydrogen, land fill gas, diesel, etc.	25 – 60 % ~ $4000/kW	Automotive, residential, commercial, light industrial.

Most of the DG technologies require power electronics interface to convert energy into grid-compatible power. The converters are compatible with the voltage and frequency with the main power grid system. This interface enhances the over-all operation of the micro-grid.

- **Controllable Loads**

The utility controls its system by bringing online or turning off generating capacity, as needed to match the load demand. Total load management is the strategy that involves concept of controlling customer controllable loads to favorably modify the system load curves in correspondence with economically available generators. This could be done as direct management (auto control of deferrable loads) or indirect management (control of end use by the customers). Often the customer load profile is re-shaped to improve power system efficiency. Micro-grid serves both electrical and thermal loads. Electric loads are often classified on basis of this concept as 1) Controllable loads 2) Uncontrollable loads and 3) Semi-controllable loads. Uncontrollable loads require power at random times; either constant or demand-instant power. Controllable loads also known as deferrable loads, on the other hand are the ones that could be directly controlled in matters of power consumption. The semi-controllable loads have intermediate energy storage loads. The operating strategy of micro-grids ensures preference to the critical loads and maintaining the net power balance. This is achieved by load or generation shedding in case of an autonomous mode of operation or by buying utility power in grid-connected mode.

Control over even small portions of the load can have significant effect on total load system performance. The main objectives of the load management operation are protection of batteries from excessive discharge and maintenance of operation of more critical loads at the expense of less critical ones. In a micro-grid, controlled sources and loads are interconnected in a manner that allows energy-balance of the system by dispatch, while the non-critical loads might be curtailed during energy shortfall or high costs.

- **Interconnection switches**

The interconnection switch ties the point of connection between the micro-grid and the rest of the distribution system. Normally grid conditions on both sides of the switch are measured for determining operational conditions. Advance technology have incorporated various power and switching functions such as protection, power switching, relaying, communications, metering etc. into a single system. The interconnection switches are designed to meet grid interconnection standards, IEEE 1547 and UL 1741 for North America.

- **Control Systems**

Local control, independent of the main grid, is the key characteristic of a micro-grid, but not always necessary. Control system is implemented by several different technologies and variable complexity [12]. The main purpose of a micro-grid's control system is to ensure safe operation in both grid-connected and islanded modes. This may be based on a central controller or as autonomous parts for each DG unit. As compared to the generators in a conventional power system, where the voltage and frequency control is done by fully controllable synchronous generators; control schemes in a micro-grid must provide local voltage and frequency regulation. In an islanded mode the micro-grid control system needs to protect the system by control the local voltage and frequency as well as absorbing the demand to supply difference. As discussed before, system stability is determined by the active and reactive power control. Micro-grids' are often defined by the existence of a central controller that allocates generation amongst the DERs and makes decision on buying and selling power from the utility.

2.1.2 Operation of micro-grids

The market strategy and economics often dictate the operation mode of a micro-grid. The micro-grid normally operates in a grid-connected mode through a 60 Hz substation transformer at the PCC. However, it is also expected to provide sufficient generation capacity, controls and operational strategies to supply at least a portion of the load, after being disconnected from the distribution system and remain operational as an autonomous (islanded) entity.

In the grid connected mode of a micro-grid, the DGs are controlled to supply a pre-set value of active power. The power system grid supplies the difference of supply (active power generated by DGs) and demand (load active power) [3], [4]. Micro-grids are often required to accommodate a specified power quality level and preference to some critical loads. Also a portion of the supply within a micro-grid comes from non-controllable resources (renewable resources). In addition to electric power, they also supply heat to its conventional power system.

2.1.3 Frequency regulation

In a power system, the generation and load in a micro-grid should always be balanced. Any mismatch in supply and demand will result in frequency variations [42]-[45]. Micro-grids are dynamic power systems with variations in loads as well as presence of non-dispatchable resources. Active power control is closely associated with frequency control and reactive power control is related to voltage control. Power system stability is determined by the constancy of frequency and voltage and hence the control of active power is one of the vital performance characteristic. Close control of frequency ensures constant speed for the induction and synchronous motors. A considerable drop in frequency results in high magnetizing currents in motors and transformers. As frequency is a common factor associated with the system components, any variation in active power demand is reflected by frequency change throughout the system.

The instantaneous variation in frequency is described by the following equation as established in [59].

$$P_{gen} - P_{load} = \frac{1}{2H}\frac{df}{dt} \quad (2\text{- }1)$$

H is the total rotating inertia of the system (generators and motors). As the load power changes, the system frequency varies and hence the generation has to be matched by the automatic controls. The frequency regulation can be categorized into primary regulation, secondary regulation or tertiary regulation [59].

In the primary regulation also known as load frequency control (LFC) the variation in power system frequency is identified by the governing systems of prime movers and the outputs of the associated turbine-generators are adjusted. To restore the frequency back to the original value, secondary regulation or automatic generation control (AGC) is implemented.

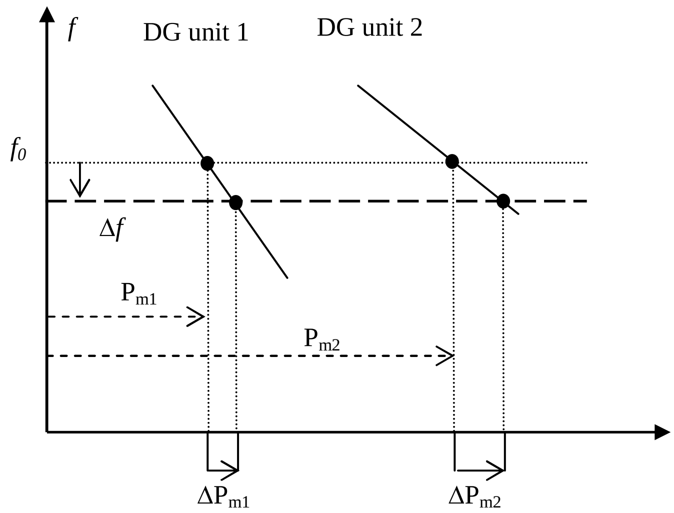

Figure 2-2 Load frequency control

The primary regulation can be expressed as load-frequency characteristics of the distributed generators are shown in figure 2-2 [1]. Initially at rated frequency f_0 the generators produced P_{m1} and P_{m2}. Upon increase in electrical load, the new steady state frequency will drop and the generator will need to accommodate the change in load. The LFC depends on the characteristics and tuning parameters of individual turbine-governor parameters.

The AGC is responsible to restore the grid frequency and most generators are equipped with this. It also distributes the required change in generation amongst units for optimal economic operation.

2.2 Power electronic transformer

An isolated high-frequency link AC/AC converter is often termed as a power electronic transformer (PET). Because of high frequency operation of the magnetic core they have size and cost advantages over conventional transformers. These transformers achieve high frequency AC power transformation without any DC capacitor link. The transformer provides isolation and voltage transformation while the power converters provide with high frequency operation. Also termed as high frequency transformers, they have been extensively researched for various applications [46]-[49], on account of many advantages over conventional line frequency transformers. The PET has a wide range of applications including electrical distribution systems, wind power generation etc. In [45]-[51] the advantages of PET over conventional transformers are discussed. Chapter 3 details the matrix converter based topology of a PET that achieves the bi-directional active power control for the micro-grid.

Chapter 3

Power Electronic Transformer

3.1 Introduction

In electric power distribution system, transformers perform several functions, such as voltage transformation, isolation, noise decoupling etc. The conventional distribution transformers operate at low frequencies (60 Hz) making them bulky and expensive. A power electronic transformer (PET) operates at much higher frequencies, of the range of several kHz. The transformer size, which is inversely proportional to the frequency and saturation flux density, could be reduced under high frequency operation conditions. The PET utilizes power electronic converters along with a high-frequency transformer to obtain overall size and cost advantages.

The PET substitutes the conventional 60 Hz transformer at the PCC of a micro-grid, connecting the later with the utility. This results in an enhanced power management for the micro-grid as well as decentralized control of the DERs and controllable loads within the micro-grid. A dynamic control of active and reactive power flow from the utility is possible. It also allows a bi-directional flow of active power between the utility and the micro-grid. The high frequency AC power transformation is achieved without a DC link.

Also a smooth transition from grid-connected to isolated mode of micro-grid is possible. To better acknowledge the claims of the PET, it is essential to understand its operation and topology, described in the following sections.

3.2 PET topology [24]

The PET consists of a high frequency transformer with three-phase to single-phase matrix converters on its primary and secondary as briefly described in chapter 1. Figure 3-1 shows a more detailed schematic of the PET [24]. The proposed topology consists of two matrix converters with high frequency AC link. The primary side of the electronic transformer is supplied by utility AC source and the secondary side has the equivalent AC source of a micro-grid. The three phase input AC voltage at the line frequency (60Hz) is first converted into high frequency (10 kHz) single phase voltage by the input side matrix converter. The output side converter is also a three phase to single phase matrix converter. This yields high frequency pulsating single phase AC voltage at the primary and secondary of the high frequency transformer with leakage reactance L_{lk}. As seen in figure 3-1 the utilities define the limit for the reference power P_{ref}, for a particular micro-grid it serves at the PCC. The average active power as measured at the output AC source can thus be restricted. By calculating the corresponding modulation signal for the secondary side matrix converter, the equivalent phase shift can be achieved. The active power flow between the input side and output side of the PET is regulated similar to that in a dual active bridge [25]. The active power flow is controlled by regulating the phase shift between the primary and secondary voltages at the transformer. The regulated phase shift angle corresponds to the desired active power limit set by the utilities. This is achieved by a PI controller designed for the control signal of the PWM strategy applied for matrix converter modulation. The proportional and integral gain parameters K_P and K_I are designed to provide a faster response while eliminating any steady state error.

The PWM strategy also allows a control over the phase shift between the voltage and current at input as well as output and hence can control the reactive power. Voltage regulation can thus be achieved by controlling the reactive power at the front-end converter.

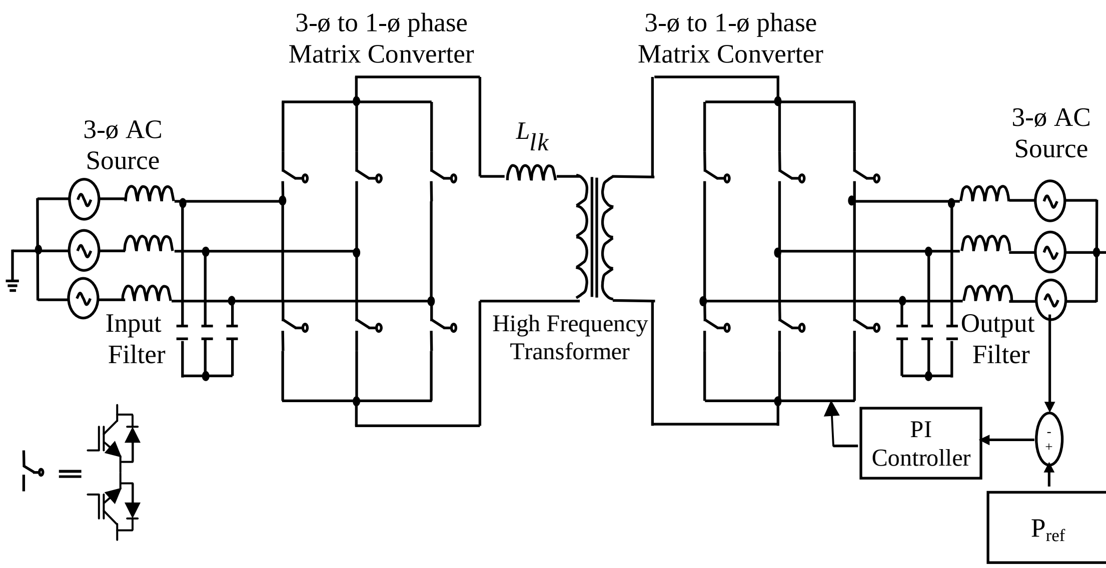

Figure 3-1 PET schematic

3.3 Matrix converter

The PET consists of matrix converters that contribute to the high frequency operation. The matrix converter [22] uses a matrix of semiconductor (IGBT) bi-directional switches, with a switch connected between each input terminal to each output terminal. They provide a direct link between the input and the output, without any intermediate energy-storage element. Such converters have several attractive features, which have been investigated in the last two decades [52], [53]. The array of controlled bi-directional switches is the main power element to create a variable output voltage system with unrestricted frequency. The dc-link capacitor is also avoided. Here a three phase to single phase matrix converter is applied to obtain an output AC voltage of desirable frequency by using six bi-directional IGBT switches.

3.3.1 Input-side matrix converter

The input-side matrix converter as shown in figure 3-2 converts the three phase AC voltage from the utility to a high frequency single phase pulsating voltage at the primary of the transformer. This is a direct link matrix converter with a conventional rectification stage followed by a single phase inverter. The input line currents are in phase with the input voltages. The matrix converter consists of six bidirectional IGBT switches.

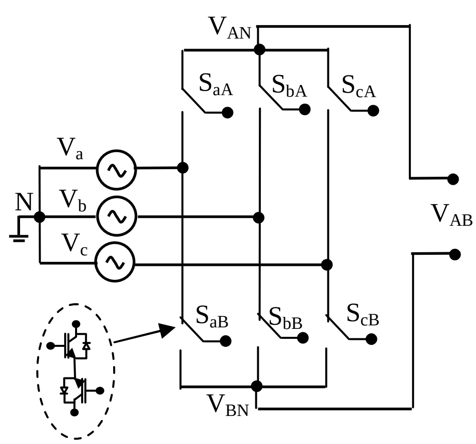

Figure 3-2 Three phase to single phase Matrix Converter

The three phase balanced sinusoidal input voltage source, with peak magnitude V_{in} and angular frequency ω_{in} is given by equation (3.1).

$$V_a(t) = V_{in}\cos(\omega_{in}t)$$

$$V_b(t) = V_{in}\cos(\omega_{in}t - \frac{2\pi}{3})$$

$$V_c(t) = V_{in}\cos(\omega_{in}t + \frac{2\pi}{3}) \qquad (3.1)$$

The single phase pulsating output voltage is given by V_{AB} .The matrix converter has 6 bi-directional switches indicated by S_{aA}, S_{bA} *and* S_{cA} corresponding to output phase-A and S_{aB}, S_{bB} *and* S_{cB} corresponding to output phase-B . The corresponding PWM signals are generated using a simple triangle comparison method [23]. Let q_{aA} be the switch state of the switch S_{aA} connecting input phase-a and output phase-A and d_{aA} be the corresponding duty ratio.

$q_{aA} = 0$; Switch turned off

$q_{aA} = 1$; Switch turned on.

Similarly, switching states q_{bA}, q_{cA} can also be defined for the output phase-A. As the input phases are connected to voltage sources, at any instant of time they cannot be shorted. Hence the switch states q_{aA}, q_{bA}, q_{cA} cannot be 1, simultaneously. Also at a time they cannot be all 0. Thus if the amplitude of the carrier is 1, then the two references d_{aA} and $(d_{aA} + d_{bA})$ are compared with the carrier for generation of the PWM, as shown in figure 3-3 as obtained from [21]. Similarly, switching signal states q_{aB}, q_{bB} and q_{cB}

for output phase-B can also be obtained. The duty ratios could now be defined with the following restrictions,

$$d_{aA} + d_{bA} + d_{cA} = 1$$

$$d_{aB} + d_{bB} + d_{cB} = 1 \quad (3.2)$$

$$0 \le d_{aA}, d_{bA}, d_{cA} \le 1$$

$$0 \le d_{aB} + d_{bB} + d_{cB} \le 1 \quad (3.3)$$

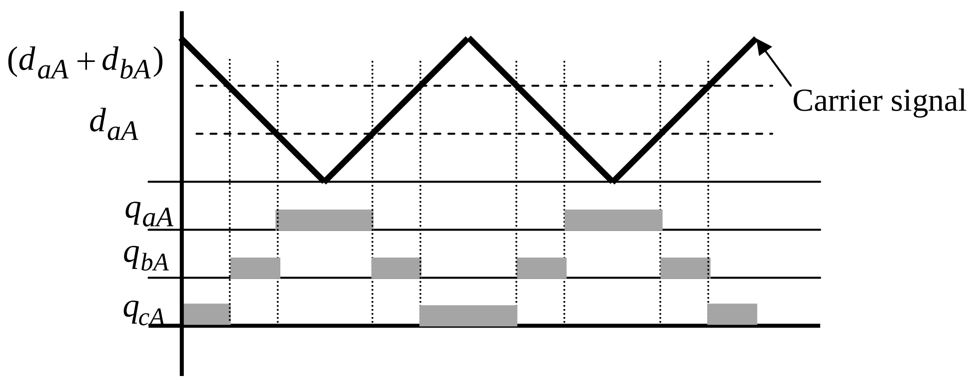

Figure 3-3 Switch states of duty ratios [21]

The duty ratios of the six bidirectional switches as derived in [8]-[10] are chosen so that the output voltage is independent of input frequency, given by (3.4) and (3.5).

$$d_{aA}(t) = k_A \cos(\omega_{in} t - \rho) + D_a(t) + \Delta_a$$

$$d_{bA}(t) = k_A \cos(\omega_{in} t - \tfrac{2\pi}{3} - \rho) + D_b(t) + \Delta_b$$

$$d_{cA}(t) = k_A \cos(\omega_{in} t + \tfrac{2\pi}{3} - \rho) + D_c(t) + \Delta_c \quad (3.4)$$

$$d_{aB}(t) = k_B \cos(\omega_{in} t - \rho) + D_a(t) + \Delta_a$$

$$d_{bB}(t) = k_B \cos(\omega_{in} t - \tfrac{2\pi}{3} - \rho) + D_b(t) + \Delta_b$$

$$d_{cB}(t) = k_B \cos(\omega_{in} t + \tfrac{2\pi}{3} - \rho) + D_c(t) + \Delta_c \tag{3.5}$$

The duty ratios of the switches are a function of $k_A(t)$ and $k_B(t)$ which are time varying signals with desired output frequency $F_s = \frac{1}{T_s}$, given by (3.6)

$$\begin{aligned} k_A(t) &= +K_i \qquad 0 \le t \le T_s \\ &= -K_i \qquad T_s \le t \le 2T_s \end{aligned}$$

$$k_B(t) = -k_A(t) \tag{3.6}$$

K_i is the modulation index of the input side matrix converter and is set to its maximum value of 0.5. Figure 3-4 shows the time varying modulation signals.

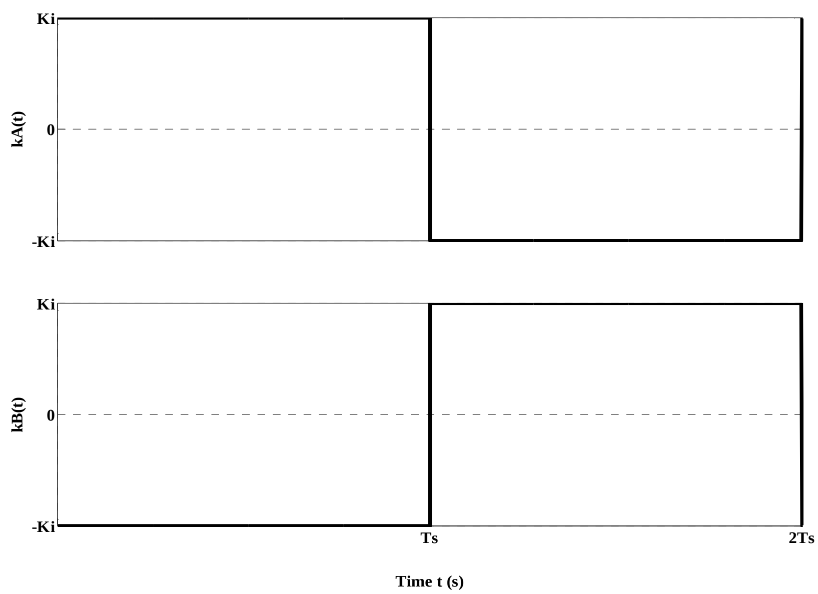

Figure 3-4 Time varying modulation signals

The term $\cos(\omega_{in} t - \rho)$ represents that the output voltage is affected by the choice of ρ and the input power factor depends on ρ. To have unity power factor operation ρ has to be chosen to be equal to zero. $D_a(t)$, $D_b(t)$ and $D_c(t)$ are the individual offset duty ratios introduced to cancel the negative components from the individual duty ratios. This satisfies equation (3.3).

$$D_a(t) = \left| K_i \cos(\omega_{in} t - \rho) \right|$$

$$D_b(t) = \left| K_i \cos(\omega_{in} t - \tfrac{2\pi}{3} - \rho) \right|$$

$$D_c(t) = \left| K_i \cos(\omega_{in} t + \tfrac{2\pi}{3} - \rho) \right| \qquad (3.7)$$

To maintain equation 3.2, it is required to inject another set of common mode duty ratios $\Delta_a, \Delta_b, \Delta_c$ corresponding to phase a, b, c is added.

Where,

$$\Delta_a(t) = \frac{1 - (D_a + D_b + D_c)}{2}$$

$$\Delta_b(t) = 0$$

$$\Delta_c(t) = \frac{1 - (D_a + D_b + D_c)}{2} \qquad (3.8)$$

The average voltage in the two output phases (A and B) is synthesized by time-weighing the three input voltages by the duty ratios as follows:

$$V_A(t) = d_{aA} v_a + d_{bA} v_b + d_{cA} v_c$$

$$V_B(t) = d_{aB} v_a + d_{bB} v_b + d_{cB} v_c \qquad (3.9)$$

Over a sub-cycle the average line to line voltage $V_{AB}(t)$ can be given as

$$V_{AB}(t) = \frac{3}{2} V_{in} [k_A(t) - k_B(t)] \quad (3.10)$$

Thus the average line to line voltage to the transformer primary is a square wave with amplitude 1.5V_{in}. The single phase high frequency pulsating voltage at transformer primary can thus be evaluated as,

$$V_{pri}(t) = \frac{6V_{in}}{\pi} \sum_{n=1,odd}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi}{T_s} t \right) \quad (3.11)$$

where V_{in} is the peak voltage of the three phase input AC voltage source and F_s is the switching frequency. The average line current in the transformer primary can also be assumed to be a square wave. The input line currents are in phase with the input voltages. The input current in a phase is represented as a function of the duty ratios and the output current.

$$i_a = (d_{aA} - d_{aB}) i_{AB}$$

$$i_b = (d_{bA} - d_{bB}) i_{AB}$$

$$i_c = (d_{cA} - d_{cB}) i_{AB} \quad (3\text{-}12)$$

Where i_{AB} is the output current of the input side matrix converter. The input current i_a is in a lagging phase of ρ with the input voltage v_a.

3.3.2 Output-side matrix converter

The output side converter, which is also a three-phase to single-phase matrix converter, converts the three phase AC voltage from a micro-grid source (DERs) to a high frequency single phase pulsating voltage at the secondary of the transformer. It is modulated in a similar fashion as the input side matrix converter, with the duty ratios of the switches derived similar to that in (3.4) and (3.5). The time varying signals $k_C(t)$ and $k_D(t)$ for output matrix converter are given by

$$
\begin{aligned}
k_C(t) &= +K_i \qquad t_p \le t \le T_s + t_p \\
&= -K_i \qquad T_s + t_p \le t \le 2T_s + t_p
\end{aligned}
$$

$$k_C(t) = -k_D(t) \tag{3.13}$$

Where K_i is the modulation index, set to maximum value of 0.5 for both the matrix converter and t_p is the phase-shift (in seconds) between the voltage, at transformer primary and secondary. The condition for the phase shift is $-\frac{T_s}{2} \le t_p \le +\frac{T_s}{2}$. The control signals $k_A(t)$, $k_B(t)$. $k_C(t)$, $k_D(t)$ and the phase shift t_p determine the modulation signals to the matrix converters in order to achieve the desired phase shift. Figure 3-5 shows the modulation signals of the input and output side matrix converters for a maximum phase shift of 90 degrees. The phase shift is given by $\frac{\pi t_p}{T_s}$ radians.

The single phase high frequency pulsating AC voltage at the transformer secondary is then given as,

$$V_{\sec}(t) = \frac{6V_{out}}{\pi} \sum_{n=1,odd}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi}{T_s}(t - t_p) \right) \tag{3.14}$$

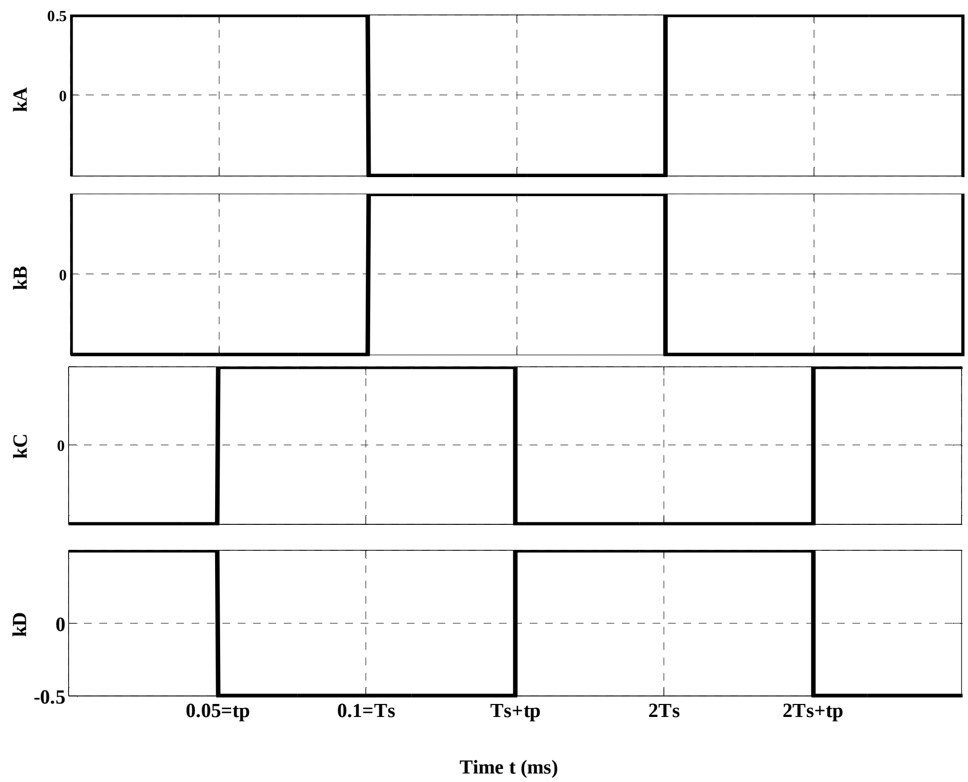

Figure 3-5 Matrix converter control signals

Thus the average line to line voltage at the transformer primary and secondary is a square wave with amplitude $\frac{3}{2}V_{in}$ and $\frac{3}{2}V_{out}$ respectively. The average current in the transformer primary and secondary are square waveforms. This strategy ensures sinusoidal input line currents in phase with input voltage.

3.4 Power flow control

The active power flow from the utility to the micro-grid is bidirectional and dynamic. The utilities can restrict the power flow to the micro-grid and dynamically change the limit. The utilities set the reference limit for the active power to be supplied to the micro-grid. Once the dynamic limit reference point is set, the PI controller provides with the associated control signal to the PWM generator of the secondary side matrix converter. This in turn regulates the modulation indices of the output side matrix converter providing a corresponding phase shifted secondary voltage. Thus, the power flow between the primary and secondary of the transformer is controlled by regulating the phase shift between its voltages.

On the other hand the reactive power control is achieved by controlling the power factor $\cos(\rho)$ in equation (3.4) and (3.5). Voltage regulation can then be achieved by controlling the reactive power. To understand the power flow strategy, the three phase AC system is simplified.

3.4.1 Simplified AC system representation

A simplified representation of the system is shown in figure 3-6, where the high frequency transformer is represented by its leakage inductance neglecting any series resistance. The average line to line voltages at the transformer primary and secondary are given by voltages sources V_1 and V_2, which are square waveforms with amplitudes $\frac{3}{2}V_{in}$ and $\frac{3}{2}V_{out}$, respectively. For a continuous power flow, the average current in transformer primary and secondary is also a square waveform.

The fundamental component of the high frequency pulsating voltages at the transformer primary and secondary voltages can be given as in (3.15)

$$V_{pri}(t) = \frac{6V_{in}}{\pi}\sin\left(\frac{\pi}{T_s}t\right)$$

$$V_{\sec}(t) = \frac{6V_{out}}{\pi}\sin\left(\frac{\pi}{T_s}(t - t_p)\right) \quad (3.15)$$

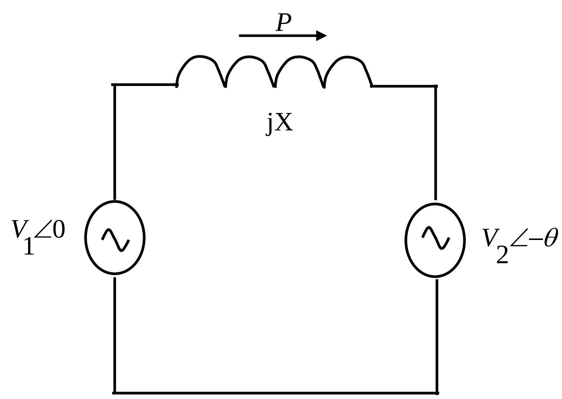

Figure 3-6 Simplified AC system

For two phase-shifted square voltages on the primary and secondary of the transformer, the active power flow can now be controlled by controlling the phase-shift t_p. The bi-directional active power can be thus defined as,

$$P = \frac{36}{\pi^2}\frac{V_{in}V_{out}}{X}\sin\left(\frac{\pi t_p}{T_s}\right) \quad (3.16)$$

Power flow control at a predefined limit P_{ref} is achieved by controlling the parameter t_p as defined by the modulating signals. The active power flow is dynamically controlled with respect to phase shift between the transformer primary and secondary. Figure 3-7 shows the power flow as a function of phase shift with maximum power transfer achieved at 90^o phase shift. Since the power flow is bi-directional both negative and positive phase shifts get considered. Also at zero phase-shift there is no power flow between the utility and micro-grid. This will be the islanding state for the micro-grid.

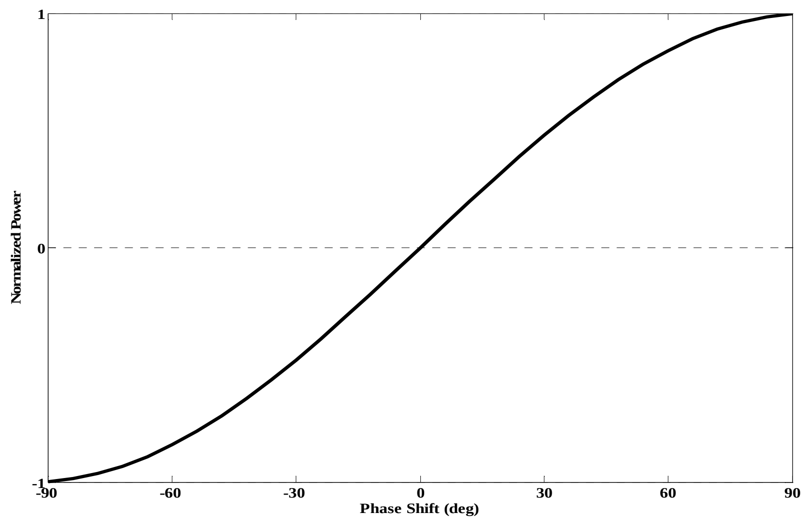

Figure 3-7 Power flow as function of phase shift

3.4.2 PI controller for active power control

The overall control system can be shown as in figure 3-8. P_{ref} is the predefined reference active power, as set by the utilities, at which the power flow is to be limited. $G_{PS}(s)$ represents the power stage of the system and $G_C(s)$ is the PI controller to be designed with proportional gain K_P and integral gain K_I, given as

$$G_C(s) = \frac{\theta(s)}{\Delta P(s)} = K_P + \frac{K_I}{s} \tag{3.17}$$

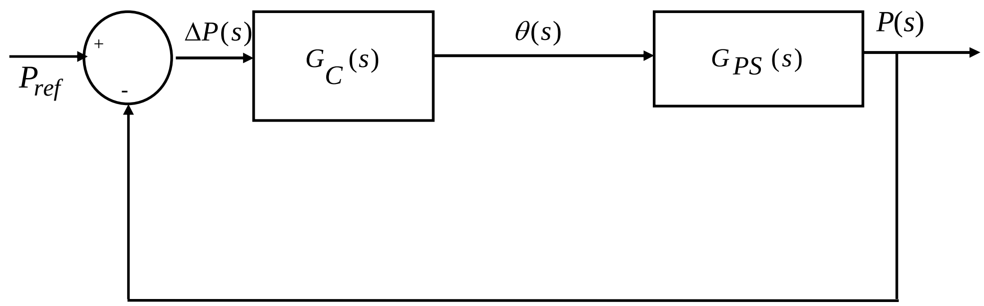

Figure 3-8 Overall control system

The power transfer function, given by (3.16) being a non linear equation is linearized over operating point θ_0 to define the power stage of the system, given by

$$G_{PS}(s) = \frac{P(s)}{\theta(s)} = \frac{V_1 V_2}{X}\cos(\theta_0) \qquad (3.18)$$

With the average of fundamental power transferred given by (3.13), the higher order harmonic component of power can be given by (3.18)

$$P_H(\theta) = \sum_{n=3,odd}^{\infty} \frac{V_1 V_2}{X n^3}\sin(n\theta) \qquad (3.19)$$

The error present due to the higher order odd harmonics (n<15) with respect to phase shift is shown in figure 3-9. It can be said that the error peaks at negligible phase shift and zero at maximum possible phase shift (90^{o}). The operating point θ_0 can be chosen considering the fact that the error stays less than 5%. For the simulations an operating point of 30^{o} is chosen for the phase shift.

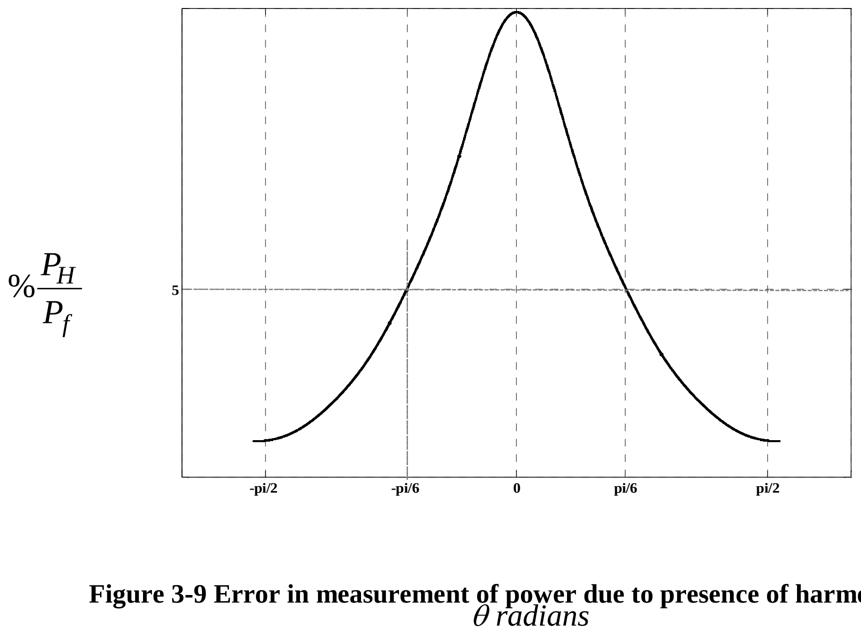

Figure 3-9 Error in measurement of power due to presence of harmonics

3.4.3 Reactive power control

Voltage profile is affected by any possible change in demand or unplanned islanding of the micro-grid. Voltage of the system can be maintained either by excitation control of generators or by control of reactive power. With the PWM strategy employed for the matrix converters in the PET, the phase lag for the input current can be controlled. This allows control of the reactive power that can flow from the utilities. The reactive power Q at the input side AC source is given by

$$Q = V\ I \sin(\rho) \tag{3-20}$$

The following section details the simulation results for the mathematical analysis established here.

3.5 Results and discussion

The PET topology is simulated in Simpower system toolbox in MATLAB/Simulink. The proposed topology is simulated for a three phase balanced input AC voltage source with peak magnitude V_{in} of 20kV and 60 Hz frequency and the three phase balanced output AC voltage V_{out} with peak magnitude of 400V and 60 Hz frequency. The bidirectional switches of the matrix converter are modulated at 10 kHz switching frequency and the modulation index K_i is 0.5. The leakage reactance of the AC link transformer is 1mH. The active power flow control and the PET operation are simulated for unity power factor. The simulation model is described in detail in Appendix A and the parameters are given n Appendix B.

3.5.1 Simulation results for the Matrix Converter

The matrix converter modulated using a novel PWM strategy [23] outputs high frequency (10 kHz) pulsating AC voltage at transformer primary. The modulation yields a maximum output voltage limited to 0.866 times the amplitude of input voltage. The average line to line voltage at transformer primary is a square wave of amplitude ≈24.5 kV (1.5V_{in}) and that at the transformer primary is ≈490V (1.5V_{out}). The primary voltage and its average are shown in figure 3-10.

The voltage and current at transformer primary is shown in figure 3-11. The currents at the transformer primary and secondary are shown in figure 3-12. Similar to that of a dual active bridge topology, the average primary and secondary current in a PET are also square waveforms. The input current is sinusoidal and has the same amplitude as the primary current (K_i = 0.5). The input current contains low frequency harmonics which could be filtered out.

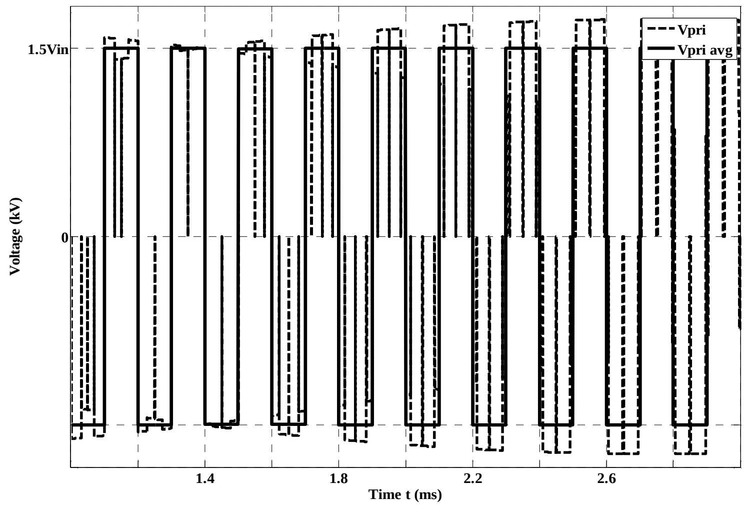

Figure 3-10 Voltage at transformer primary

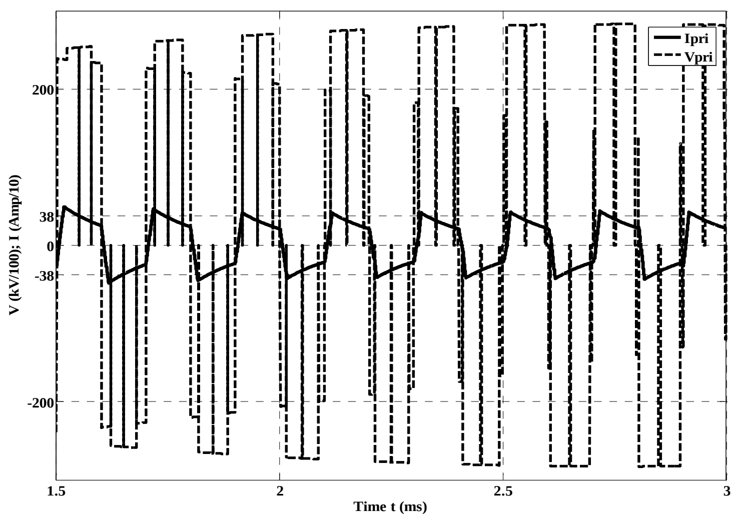

Figure 3-11 Voltage and current at transformer primary

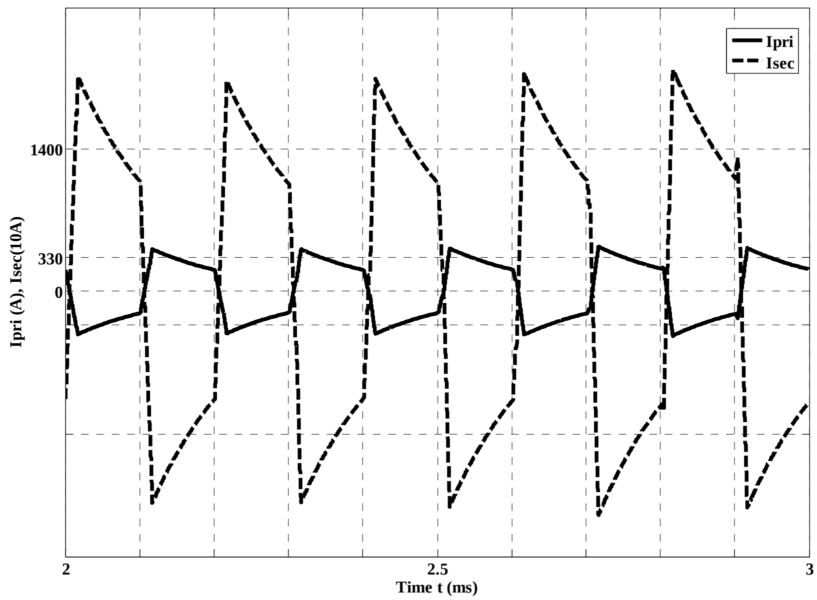

Figure 3-12 Currents at transformer primary and secondary at 30° phase shift

The input line current in phase-*a* is in-phase with input voltage. The simulated filtered input current waveform is shown in figure 3-13. There is negligible power factor due to the filter inductance. Also figure 3-14 shows the secondary side source voltages and current. It is assumed that there is no power loss and hence the average active power on the secondary is same as that in the primary. It can be seen that the input and output currents both contain low frequency harmonics. Also to be noted that the amplitude of the output currents of both the matrix converter being square waveforms the corresponding source currents are sinusoidal and have the same amplitude as the average currents in transformer primary and secondary. The power factor could be controlled to achieve the reactive power control capability of the PET.

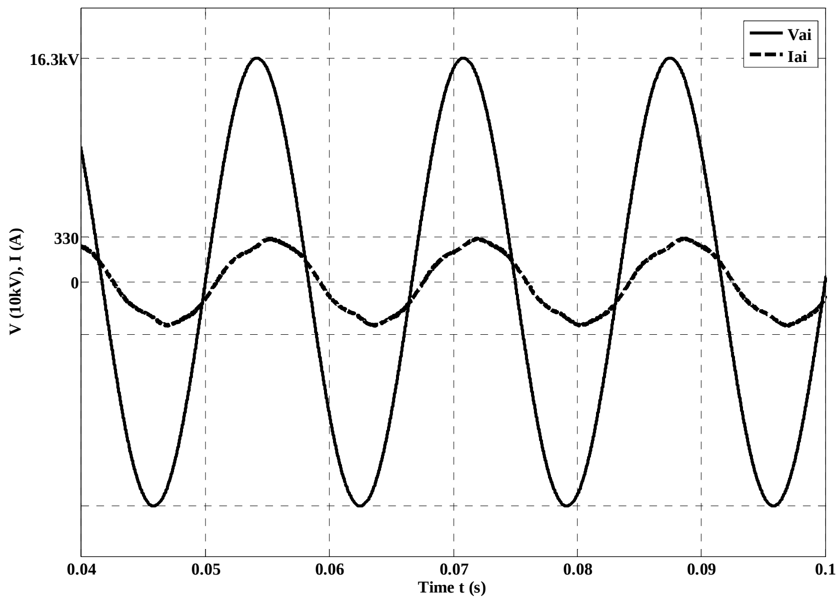

Figure 3- 13 Voltage and current for input phase a

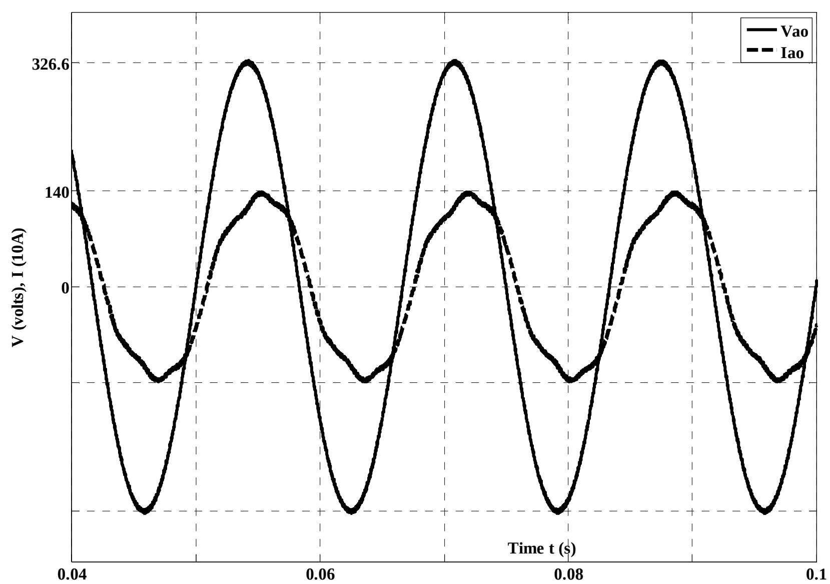

Figure 3-14 Voltage and current for Output phase a

The modulation indices $k_A(t)$ and $k_B(t)$ for the input side matrix converter are a time varying signal with desired output frequency (10kHz). Similarly $k_C(t)$ and $k_D(t)$ are modulation indices for output side matrix converter. A phase shift between the modulation indices of input and output side modulation indices reflects in corresponding phase shift between the primary and secondary voltages of the transformer.

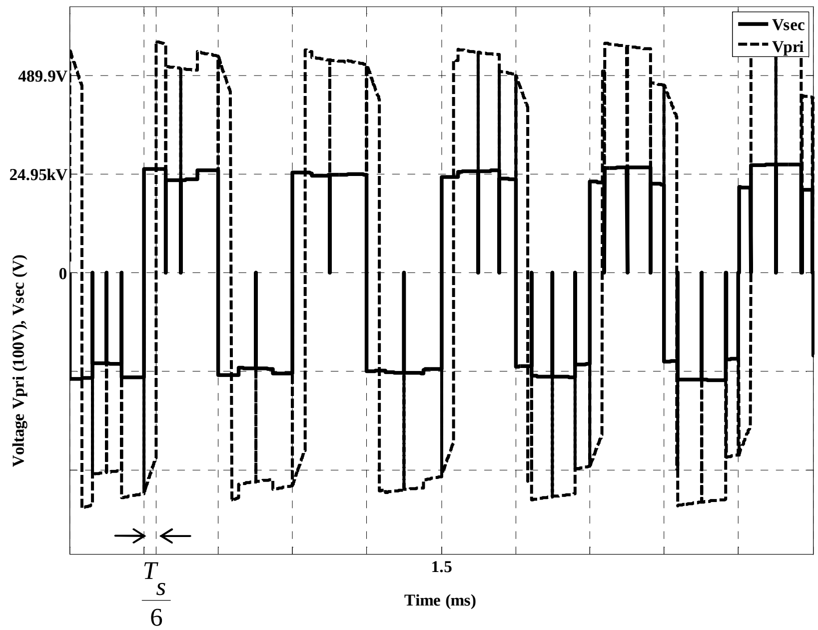

Figure 3-15 Voltage at transformer primary and secondary at 30^o phase shift

The voltage at the secondary of the transformer is phase shifted with respect to the primary voltage. Figure 3-15 shows the voltage profile at 30^0 phase shift and figure 3-14 is at 60^o phase shift. The primary-side matrix converter and the secondary-side matrix converter are both modulated at a high frequency of 10 kHz, with similar output voltage profile, except that they are phase shifted. The matrix converters are modulated with a novel PWM strategy where the output voltage of the matrix converter is independent of the input frequency. The results also verify the average line to line voltages at the primary and secondary are 1.5V_{in} and 1.5V_{out} respectively.

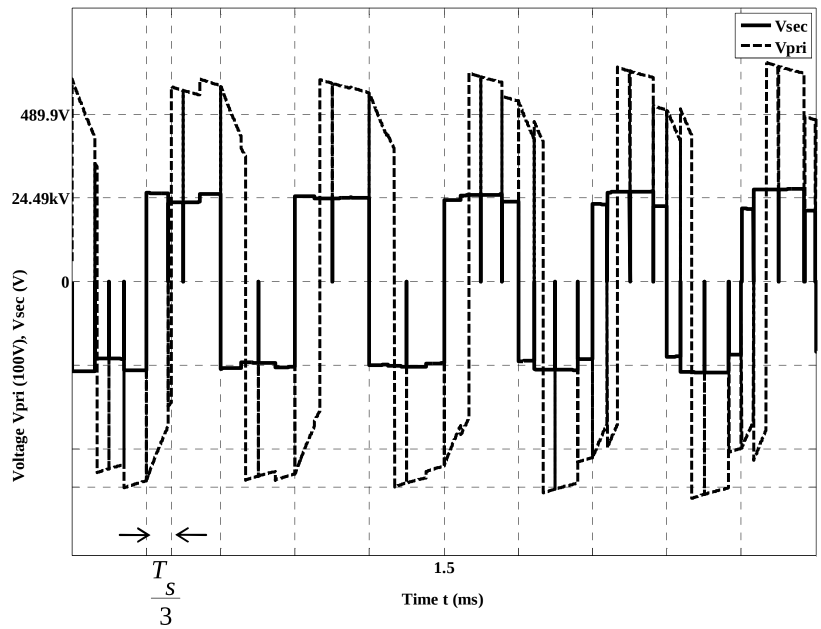

Figure 3-16 Voltage at transformer primary and secondary at 60^o phase shift

3.5.2 Simulation results for Active Power control

In the event of sudden load change in the micro-grid, the active power flow at the PCC varies significantly which may be undesirable during the peak load demand from the power system grid. A case study for the performance of the PET under different power transfer conditions is studied. The power flow between the transformer primary and secondary is controlled by regulating the phase shift between the high frequency pulsating AC voltages. For the simulated system a maximum power (10 MW) is transferred at 90^o phase shift and the micro-grid is islanded at 0^o phase shift. Figure 3-17 gives the profile of average active power flow at various instances with different phase shifts as determined by the utilities. Initially the utility is supplying with maximum grid supply. Upon a phase shift applied to the secondary side matrix converter, the grid power is now restricted to 40% of the maximum.

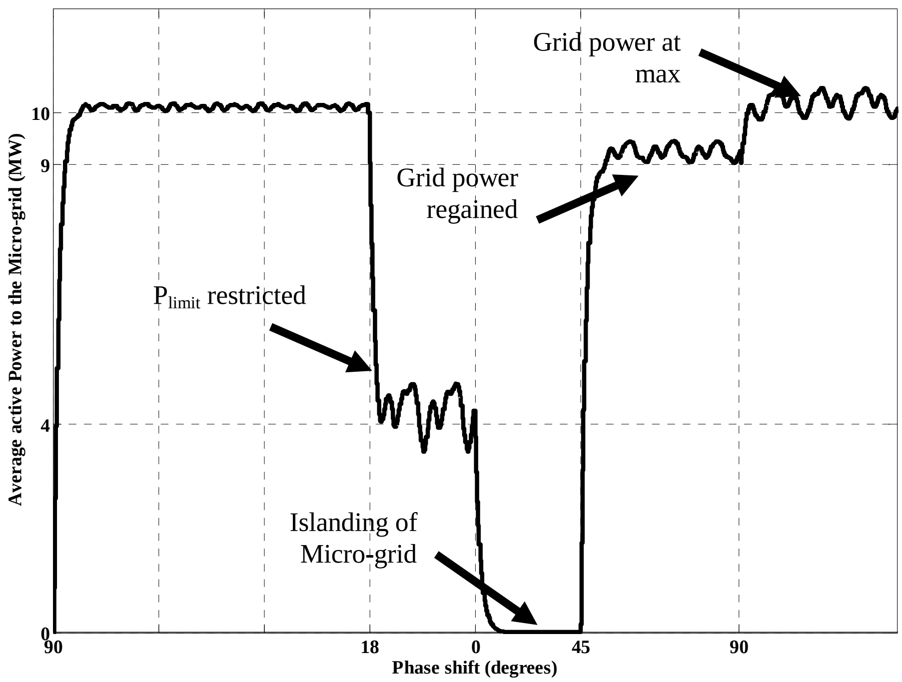

Figure 3-17 Power flow as a function of phase shift

In occurrence of any fault or during an intentional islanding the grid power reduces to zero and the micro-grid becomes responsible to match its internal generation with demand, either by increasing the generation or reducing the consumption. Later the micro-grid regains its grid power as planned by the utilities. Thus a dynamic limit could be set by the utilities to control the power that may flow at the PCC. Another case of dynamically changing active power flow at the PCC is considered. Here the bi-directional power flow capability of PET is established. A negative average power denotes the power transfer from the micro-grid to the utilities. The utilities can thus utilize the renewable sources integrated within the micro-grid which could be established as one of the market strategy for such distribution system for economical as well as environmental benefits. This result also substantiates the PET capability to allow participation of the micro-grid components in grid frequency restoration.

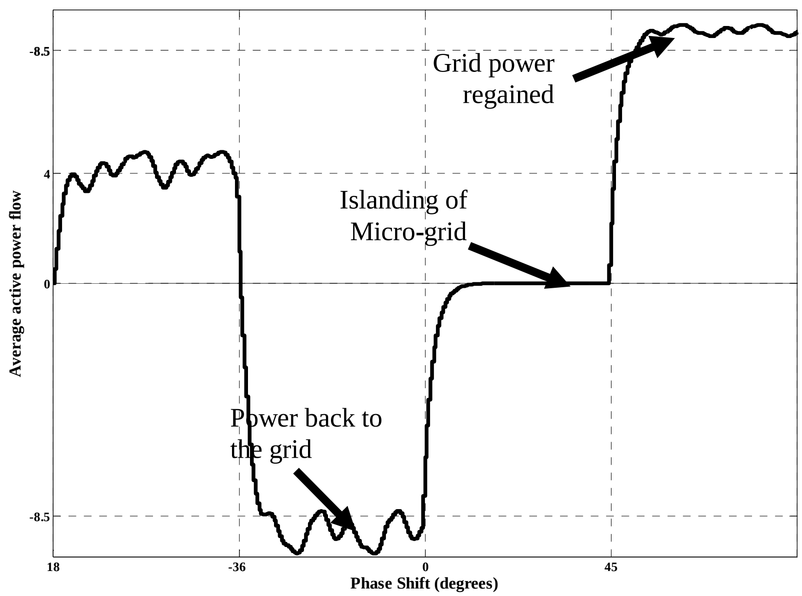

Figure 3-18 Power flow as function of phase shift

As shown in figure 3-18 the system is operating with power transfer from the utilities to the micro-grid at 18^o phase shift. At certain instant of time the utility starts buying power from the micro-grid (phase shift of -36^o), is also shown. The power transfer is zero for a planned islanding of the micro-grid after which the grid power is regained.

The non-linear power transfer equation given by (3.16) is linearized over operating point θ_0 of 30^o. A feedback controller is required to process the error as the difference between the desired power limit and the actual measured average power and attempt to minimize the error. The proportional gain helps achieve a faster response to the step change and the integral gain reduces the steady state error. The PI controller is designed with a proportional gain constant K_P of 0.01 and K_I integral gain constant of 0.5. A step change of 5 MW to 3 MW in reference power yields a step change in the phase shift from 30^o to 35^o , thus restricting the power flow. The simulation result shown in figure 3-18 verifies that the power flow can be now controlled for a predefined dynamic limit as set by the utilities.

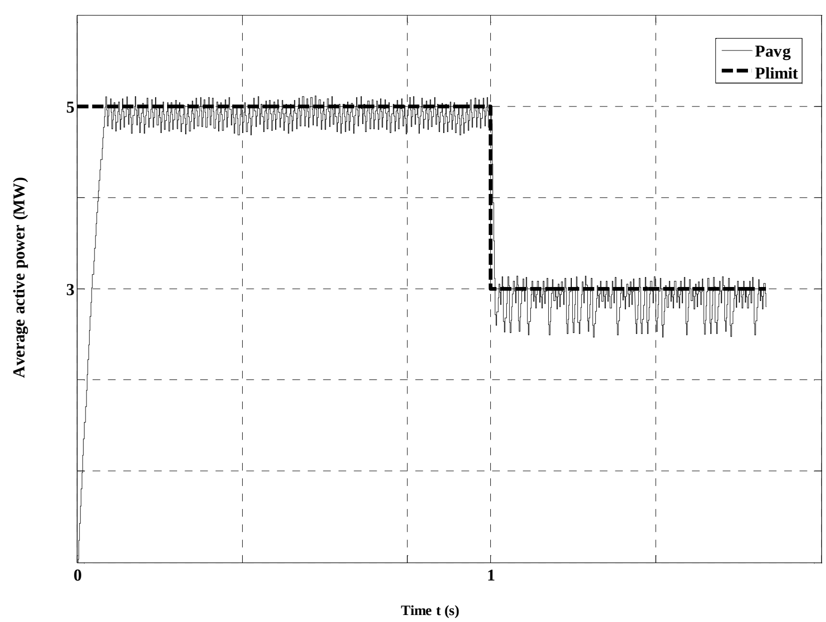

Figure 3-19 Active power flow control

When the secondary side AC source (aggregated microsources of a micro-grid) experiences a restricted power flow, the micro-grid experiences change in its state of operation. That is, it may experience a temporary drop in total generation to match with its internal demand. The secondary side AC source may now operate at a different frequency than the input side AC source. PET also ensures that any disruptions in frequency in the micro-grid will not affect the grid frequency on the input side of the transformer.

3.5.3 Simulation results for Reactive Power control

Due to possible load disruptance and network outages, the frequency at the PCC constantly varies. Also due to restriction in active power at the PCC by the PET, the grid frequency may drop. This affects the voltage profile at the transformer primary. The PET modulation strategy allows control over reactive power which hence controls the voltage. The PET achieves voltage regulation by control of reactive power. As studied in section 3.3 the PWM strategy employed for PET operation allows control over the phase lag between the input current and input voltage of the matrix converter. This in turn allows control of the reactive power that may flow in the system resulting in voltage regulation. Figure 3-20 studies the variation in the reactive power at the utility side matrix converter due to a step change in the phase lag at time t=40ms. The resulting input voltage and current are shown in figure 3-21. Initially before t=40ms the input current is in phase with the output voltage. There power factor is not exactly unity due to the filter inductances. Later when the modulation strategy employs a phase lag of 15^{o}, the resulting lag in input current is shown These results substantiate the capability of the PET to be able to control the reactive power that could be injected at the primary side of the PET resulting in voltage regulation. For a stable interconnected power system it is essential that the system frequency and voltage are regulated. The stability of system frequency is achieved by control of active power and the voltage regulation is achieved by control of reactive power. The PET proves its capability to regulate both the system frequency and input voltage.

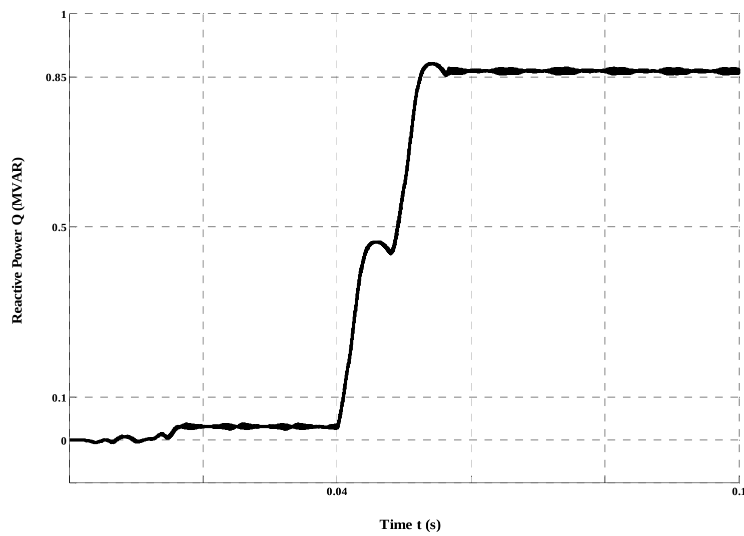

Figure 3-20 Reactive power control

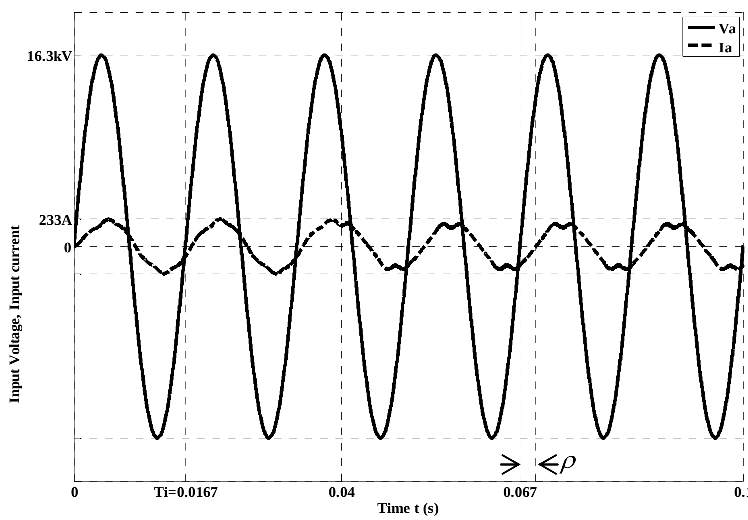

Figure 3-21 Input voltage and current

3.6 Chapter summary

With the dynamic power limiter proposed in this paper, the active power flow from the grid can be controlled at the PCC of a micro-grid to a desired value, determined by the utilities. The proposed PET allows power management with a dynamic limit as well as bi-directional power flow. This chapter established the detail operation of the PET. Simulation results are explained that support the claims of PET. Some of the Simulink files are given in appendix A. The values of the parameters of the PET schematic and detailed results are given in appendix B.

Note: Portion of this chapter is reproduced from my IEEE publications [24],[54-55]

Chapter 4

Decentralized System Control

The concept of high frequency AC link is further explored for its suitability in power distribution system such as that in a micro-grid. The PET, as explained in chapter 3, claims to restrict the active power flow to a micro-grid, at a desired value determined by the utilities. The topology allows utilization of change in local grid frequency, to dynamically control the active power generation as well as consumption within the micro-grid. To meet with constantly varying load demand and possible outages, the system voltage and frequency are thus controlled by the PET. Power flow control should be achieved such that it ensures reliability, affords economy of operation using optimum generation and uses low cost generation [1]. The control of active power and reactive power is vital for satisfactory performance of power systems and hence the frequency and voltage should remain nearly constant [41]. This chapter explains modeling of various components of the system, as well as the overall system design [54], [55] to analyze the decentralized control strategy. This includes the DERs and the controllable loads that operate synchronously, to supply the demand within the micro-grid. The capability of power flow control from the power system grid thus offers an extra degree of freedom which can be used to improve the market strategy and deregulation inside the micro-grid. The chapter defines the PET's approach to regulate the frequency of the micro-grid by decentralizing the control of its components. The design strategy to allow the microsources and the controllable loads participate in the utility grid frequency restoration by adjusting the internal generation and consumption of the micro-grid by the PET is established. Also further, the participation of micro-grid components in grid frequency restoration is verified.

4.1 System design

A micro-grid can operate smoothly by controlling the generating capacity as needed to match the load demand. Also presence of controllable loads in the micro-grid, allows control over small portions of loads thus maintaining operation of critical loads, without totally turning off power supply to any particular load. Constant frequency and voltage determine the quality of power supply to the consumers. This ensures constancy of speed of induction and synchronous motors [56], [57]. The frequency of systems is dependent on active power balance. As frequency is a common factor throughout the system, a change in active power demand at one point is reflected throughout the system by a change in frequency [58], [59].The control of generation and frequency can be achieved by load frequency control (LFC), while optimum generator operation is achieved by automatic generation control (AGC). A speed governor on each DG unit provides the primary speed control function (LFC), while the supplementary control (AGC) allocates generation.

When there is a load change, it reflects instantaneously as a change in the electrical torque output T_e of the generator. This in turn results in speed variations as determined by the equation of motion. On the other hand, power system loads are composite of a variety of electrical devices. For resistive loads, such as lighting, the electrical power is independent of frequency. In the case of motor loads, such as fans, the electrical power changes with frequency due to changes in motor speed. Figure 4-1 illustrates power flow control in a micro-grid consisting of several DERs (dispatchable or non-dispatchable) and loads (controllable and non-controllable). The PET allows a restricted active power supply P_{grid} from the main power grid to the micro-grid, at the PCC. The dynamic limit is set by the utilities. The micro-grid is characterized into its major components: DERs and loads. The DERs are further categorized into renewable and non-renewable resources. For the system design, it is considered that the renewable resources (wind, PV array, etc.) are designed to operate at their optimal generating point. This also emphasizes micro-grids ability to best utilize the renewable resources. The non-renewable resources (microturbines etc.) are the ones that play role in increasing or decreasing the generation upon variations in the grid power supply. The loads of the micro-grid are also categorized into controllable or non-controllable, critical or non-critical. The controllable loads play their role of decreasing the system demand to accommodate frequency stabilization. Since the generation and consumption of the micro-grid is controlled at the PCC by the PET, with change in frequency as the parameter, the system can be said to have decentralized control.

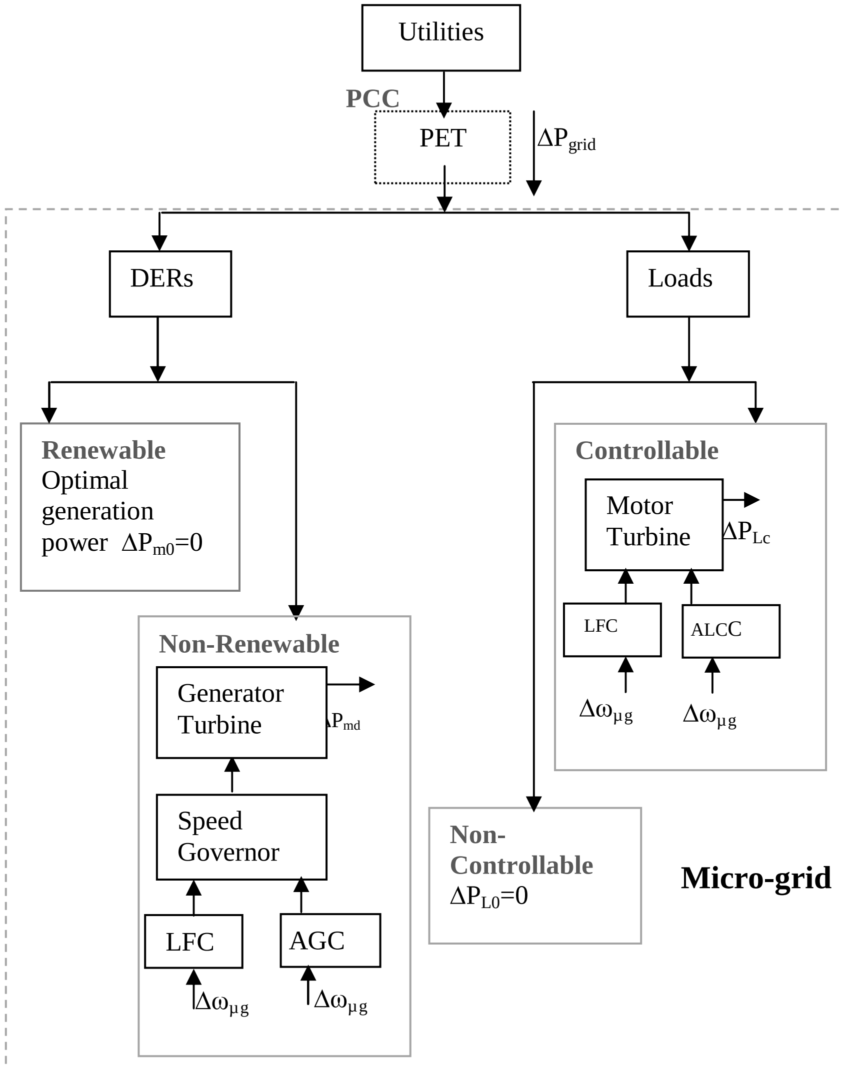

Figure 4-1 Micro-grid system design

Figure 4-1 also gives the parameters involved in the variation of power flow at system level. The DGs within the micro-grid provide with total mechanical power $P_{m,d} + P_{m,0}$. $P_{m,d}$ is the mechanical output power from G dispatchable DG units and $P_{m,0}$ is the output from G_0 non-dispatchable units. The non-dispatchable units (wind, PV array etc.) are assumed to operate at optimal conditions providing the maximum output generation and hence $\Delta P_{m,0} = 0$. So, the effective component of change in prime-mover mechanical power $\Delta P_{m,0}$ for a micro-grid system, produced by the governor-controlled valve motion [60] can be given as,

$$\Delta P_{m,d} = \sum_{k=1}^{G} \Delta P_{md,k} \tag{4.1}$$

$$\Delta P_m = \Delta P_{m,d} + \Delta P_{m,0} \tag{4.2}$$

Similarly, the total load consumption is given by $(P_{Lc} + P_{L0})$ where P_{Lc} is the total load demand of L controllable loads and P_{L0} is the demand of non-controllable. For non-controllable loads that may or may not be critical ΔP_{L0} may experience a sudden disruptance changing the overall system demand. The total load change ΔP_L can be given as,

$$\Delta P_{Lc} = \sum_{k=1}^{L} \Delta P_{Lc,k} \tag{4.3}$$

$$\Delta P_L = \Delta P_{Lc} + \Delta P_{L0} \tag{4.4}$$

The DG units need to match the load demand within the micro-grid and hence, upon any sudden load disturbances or change in grid supply, equation (4.5) should be satisfied.

$$\Delta P_L = \Delta P_m + \Delta P_{grid} \tag{4.5}$$

The power system grid supplies with the difference in active power generation by the DG units and the load demand within the micro-grid. With a restricted power flow at the

PCC, the DGs now need to regulate their generation and the loads can also regulate their consumption. A power system's response to a load change is determined by its inertia constant (M) and the damping constant (D) [56], [57], [60]. These variables take into account both, the generators and the loads to produce an equivalent system characteristic. The damping constant D is expressed as a percent change in load for one percent change in frequency. Here, for the micro-grid, consisting of power electronics based DG units and loads, the coherent response of all generators, to changes in the system load is represented by an equivalent inertia constant M. Similarly the effect of system loads are lumped into a single damping constant D. In case of a sudden change in the dynamic limit P_{grid} set by the utilities, active power mismatch may change the frequency of the micro-grid, $\Delta\omega_{\mu g}$ This is locally sensed by the LFC and AGC controls, of the DG units as well as the controllable load units, to regulate their generation and consumption, respectively. Before the system model is established, each component of the micro-grid is modeled individually in the following sections.

4.2 Modeling system components

The performance of the micro-grid as applied to the claims of the PET is to be verified. With the basic understanding of the system and its components from section 4.1, the micro-grid is now interpreted as interconnected power systems that operate synchronously to provide active power flow to the specific group of loads. The steady state performance of such an interconnected power system is highly influenced by the speed-governing system characteristics and supplementary controls. A speed-governor system commonly consists of the speed governor, speed control mechanism and the governor controlled valves [60]. Figure 4-2 gives a schematic representation of the main elements of a speed-governor system. Here the speed governor is responsive to the speed and influence the other system elements. The speed control mechanism mainly consists of the relays, servomotors, amplifying devices, levers and linkages, valves etc. The governor-controlled valves control the energy input to the turbine and are actuated by the speed governor. The block diagram in figure 4-3 [60] illustrates the equations of performance of the system and illustrates the feedback loops involved. The inputs to the speed-governing system are the speed signal and the speed-changer position. These signals call for changes in the governor-controlled valve position which will change the input to the turbine. The change in steam flow or input to the turbine causes a change in turbine torque. The characteristics of the entire power system, the load torque and the turbine torque together determine the system speed. The power system characteristics are defined by the effective rotary inertia M and damping torque co-efficient D (loads and generators)

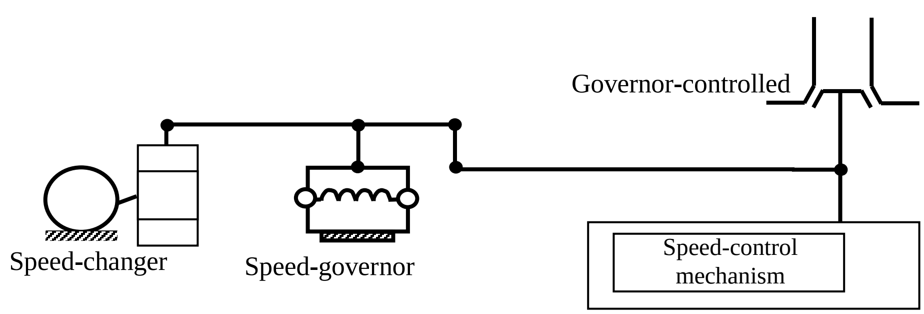

Figure 4-2 Schematic representation of speed-governing system
Source: Adapted from [60]

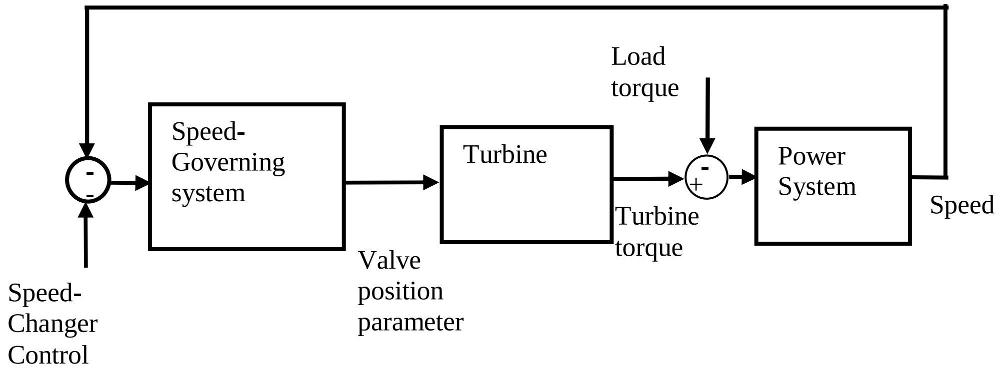

Figure 4-3 Block-diagram representation of isolated power system

Source: Adapted from [60]

4.2.1 Modeling distributed generators

The block diagram representation of an isolated area as given in figure 4-3 is used to model the DGs of the micro-grid. The dynamic response of non-reheat turbines may be approximated by a single time lag τ_t . τ_g is the governor time lag. As shown in figure 4-4, the inputs to the speed governing system with time constants τ_g and τ_t are the deviation from normal frequency Δf and supplementary controls (AGC). The reference power P_{ref} (here P_{limit} set by the PET) is an input to the power system block set along with the change in turbine torque ΔP and load torque ΔL . The power system in is defined by the quantity M which is directly related to the inertia related parameter H used in stability studies and D, the damping coefficient of the power system. [56], [60]. The input to the system is the difference between the supply and demand in that system. The resulting change in system frequency, $\Delta\omega = d\theta / dt$, is fed back to the speed governing system.

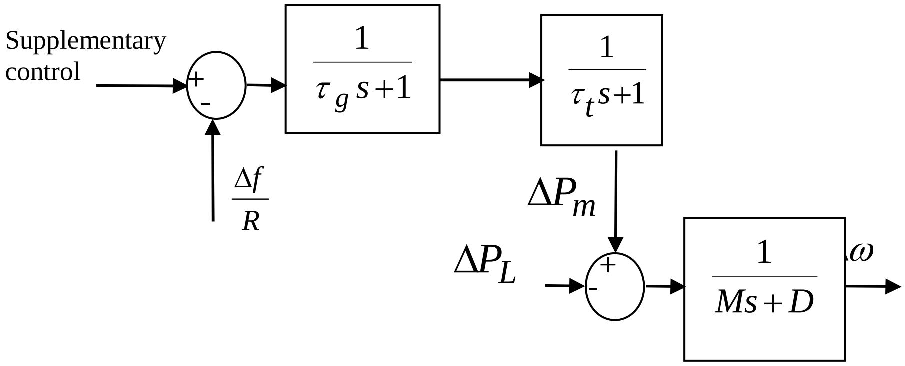

Figure 4-4 Mechanical torque input from a DG unit

Summing up the torques acting upon the inertia of the power system [60]

$$M\frac{d^2\delta}{dt^2}+D\frac{d\delta}{dt}=\Delta P_m-\Delta P_L=\Delta P \qquad (4.6)$$

Where, ΔP_m is the mechanical torque produced and ΔP_L is the load demand of the system. The model holds true for steady state analysis of dispatchable generators of the micro-grid. The non-dispatchable generators are modeled to give a fixed output or up to maximum allowable change in their generation.

4.2.2 Modeling loads

Controllable loads can be seen as negative generators with single time constant and hence, the block diagram representation is similar except sign changes. Also notice that the change in load demand is modeled. The controllable loads have power electronics to sense the change in system frequency to dynamically reduce or increase its power consumption, to meet with the energy generation.

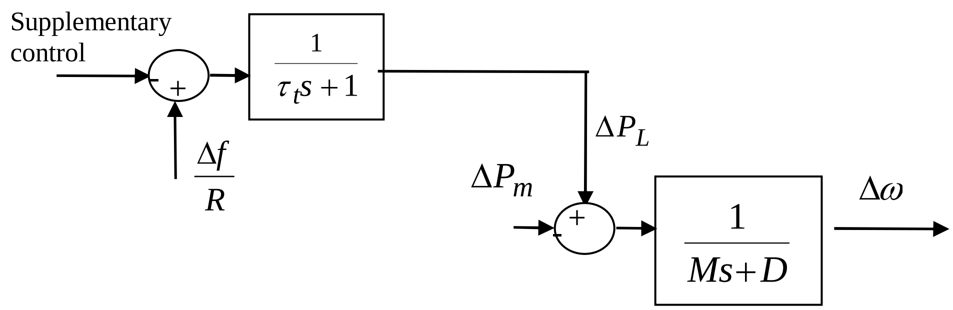

Figure 4-5 Load torque input from controllable loads

The power consumption can then be given by

$$M\frac{d^2\delta}{dt^2}+D\frac{d\delta}{dt}=\Delta P_L-\Delta P_m=\Delta P \tag{4.7}$$

4.2.3 Load frequency control

For the DG units, with drooping governor characteristics, there will be a unique frequency at which they will share a load change [56], [1]. When the load increase causes the units to slow down, the governors increase output, until they reach a new common operating frequency f'. The amount of load picked up by each unit depends on the droop characteristics, R of the units. Restoration of system frequency to nominal value f_0 is achieved by AGC. The load-frequency characteristics [56], [1] of the equivalent DG unit with droop characteristics R_{eq} and equivalent controllable load with a similar speed regulation constant R'_{eq}, is shown in Fig. 3. Initially at rated frequency f_0 the DG units produced P_m mechanical output power (point a). A sudden decrease in grid supply, and hence a mismatch in active power flow in micro-grid is reflected by change in local grid frequency. The DG units need to accommodate the change in load by regulating their generation by ΔP_m . For a controllable load, initially consuming P_L at rated frequency f_0 (point b) with the drop in frequency as a feedback signal, the power consumption could be reduced by ΔP_L . At steady state the DG units operate at a' and the loads return to their initial operating conditions at b. In the analysis, the collective performance of all generators in the systems is studied. The composite power/frequency characteristic of a power system thus depends on the combined effect of the droops of all generator speed governors and on the frequency characteristics of all the loads in the system.

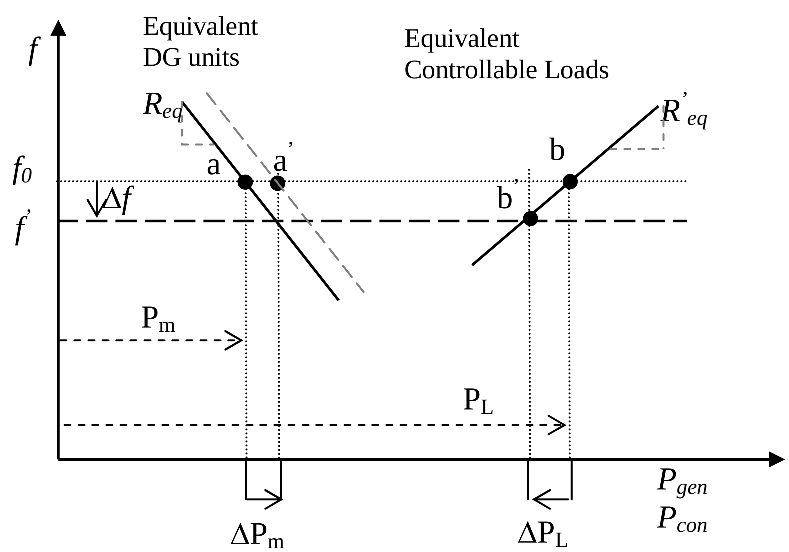

Figure 4-6 Load-frequency characteristics of DG units and loads

Considering a load disturbance in the system, the non-controllable loads (critical or non-critical) may increase or decrease the system demand and hence $\Delta P_{Lo} \neq 0$.

Renewable sources allow no control over generation and hence $\Delta P_{mo} = 0$. So from equations (4.2) and (4.4) we have $\Delta P_m = \Delta P_{md}$ (4.8)

$$\Delta P_L = \Delta P_{LC} + \Delta P_{Lo} \quad (4.9)$$

Equation 4.5 can be now written as

$$\Delta P_{grid} + \Delta P_m - \Delta P_{LC} = \Delta P_{Lo} \quad (4.10)$$

If the equivalent regulation constant of all the non-dispatchable generators be given by R_{eq} and that of the controllable loads as R_{eq}' , as shown in the figure 4-6 then for Δf drop in system frequency,

$$\Delta f = -R_{eq}\,\Delta P_m \quad (4.11)$$

$$\Delta f = R_{eq}'\,\Delta P_{LC} \quad (4.12)$$

$$\Delta f = -R_{eq}\Delta P_m = R_{eq}'\Delta P_{LC}$$

Equations 4.11 and 4.12, verify that for a stable system if the regulation constants for the non-dispatchable loads and controllable loads are equal but opposite in signs, then

$$\Delta P_m = \Delta P_{LC} \quad (4.13)$$

The equivalent droop characteristic of the generators and the loads of the micro-grid, are then mirror images to ensure system stability.

4.2.4 Automatic generation control

As the load demand fluctuates, continuously and randomly, the real power being generated must be adjusted to meet with the instantaneous change in load [1]. Most generators are equipped with AGC. Here to maintain the frequency constant, supplementary controller signals act upon the speed-changer position. For a the n^{th}

generator G_n with regulation constant R_n , the frequency bias constant B_n is given as $B_n = D + \frac{1}{R_n}$. Figure 4-7 shows the block diagram for the supplementary control provided to the DG units.

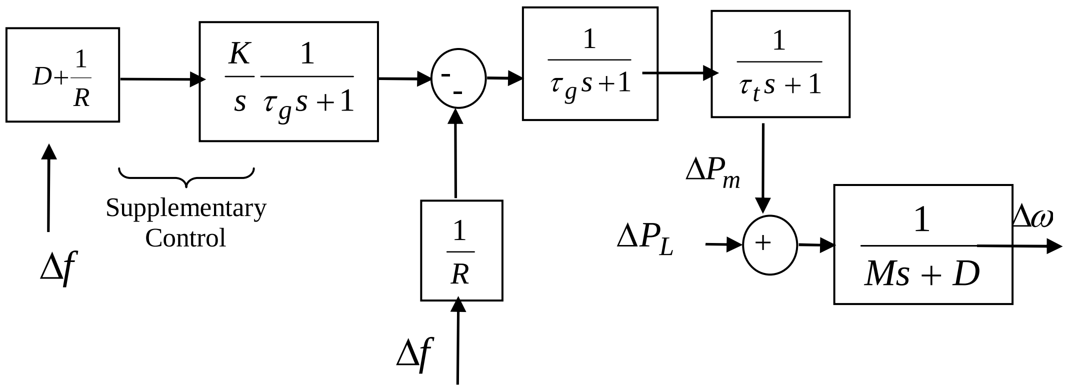

Figure 4-7 Automatic generation control

4.2.5 Automatic load control

The micro-grid consists of controllable loads and hence the consumption within the micro-grid can be controlled up to some extent. For steady state analysis the controllable loads are modeled as negative generators with single time constants. Similar to AGC, automatic load control (ALC) assigns frequency bias constant to the corresponding speed governor of the controllable load. As shown in figure 4-8 the ALC constitutes the supplementary control. It also plays an important role in participation of micro-grid during utility frequency restoration, thus integrating smart energy efficient appliances in the energy management system.

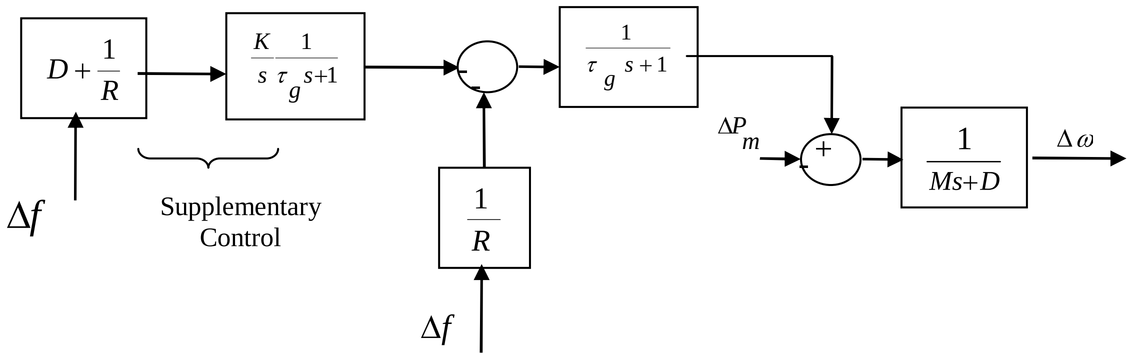

Figure 4-8 Automatic load control

4.3 System design and analysis

The component models established in the previous sections can now be extended to a more general system level design. Micro-grid modeling has been discussed in [62]-[68]. A micro-grid system is modeled in figure 4-9 with *i* controllable loads and j dispatchable DG units. The total change in generation from dispatchable DG units is given by ΔP_m. The aggregate fixed generation from non-dispatchable DG units is given by ΔP_{mo} (=0). The total variation in consumption by controllable loads is given by ΔP_{LC} . The aggregate non-controllable consumption is given by ΔP_{Lo}. Each of the DG unit and controllable load is supplied with corresponding primary and supplementary frequency control and the components respond to the change in grid frequency independently.

The grid power is the final input going to the system dynamics. The PET limits the grid power flowing into the micro-grid ensuring frequency regulation of the grid. As a result of which, the micro-grid system dynamics generate the frequency drop which is fed to the micro-grid components to regulate their generation or consumption. The micro-grid system dynamics are defined by inertia related parameter M and damping factor D of its components (DG units as well as loads).

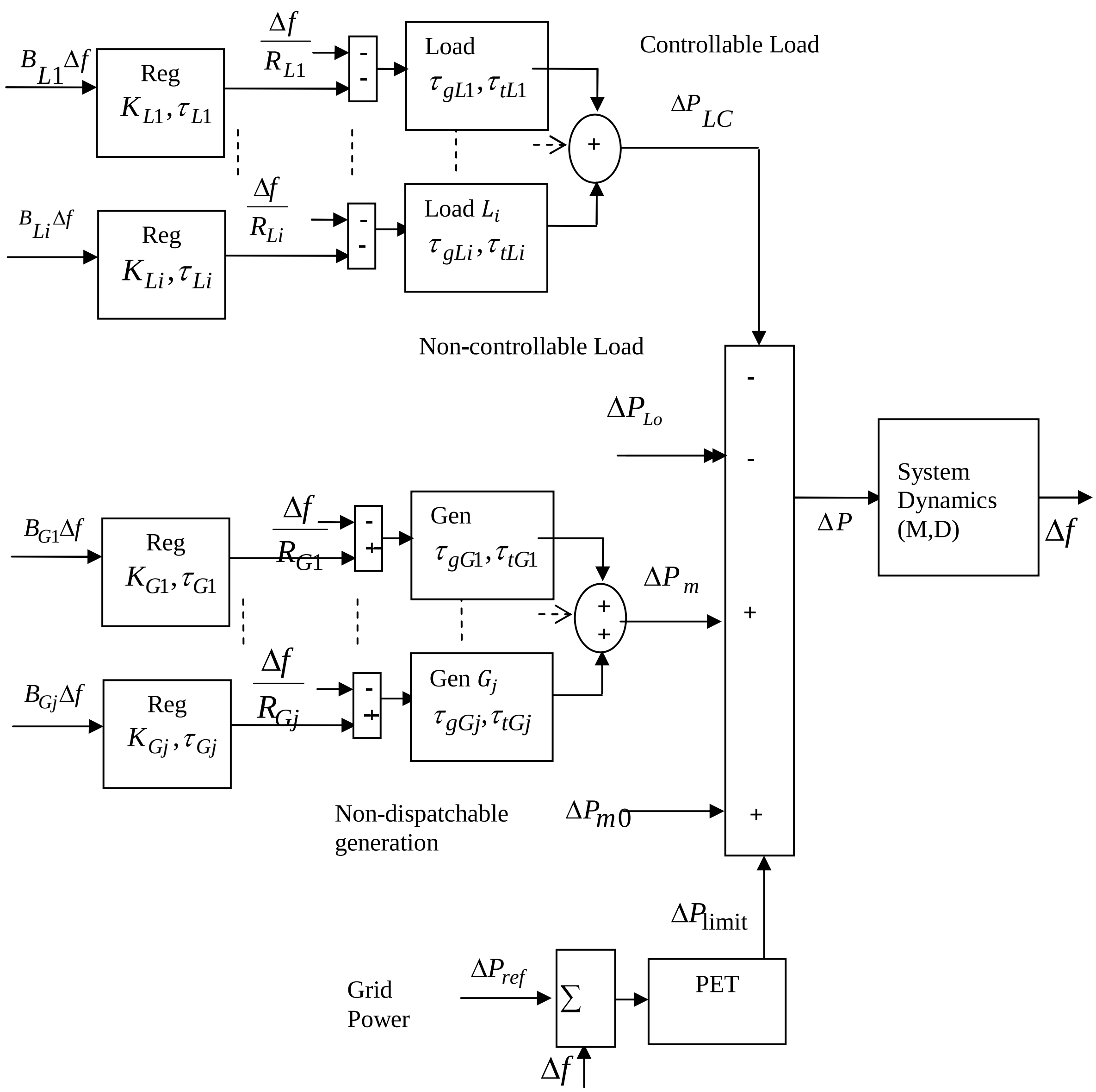

Figure 4-9 System design

of the utiltity with the micro-grid. The PET also allows the micro-grid component to participate in utility system frequency restoration. Figure 4-10 details the representation of the two AC systems in similar fashion.

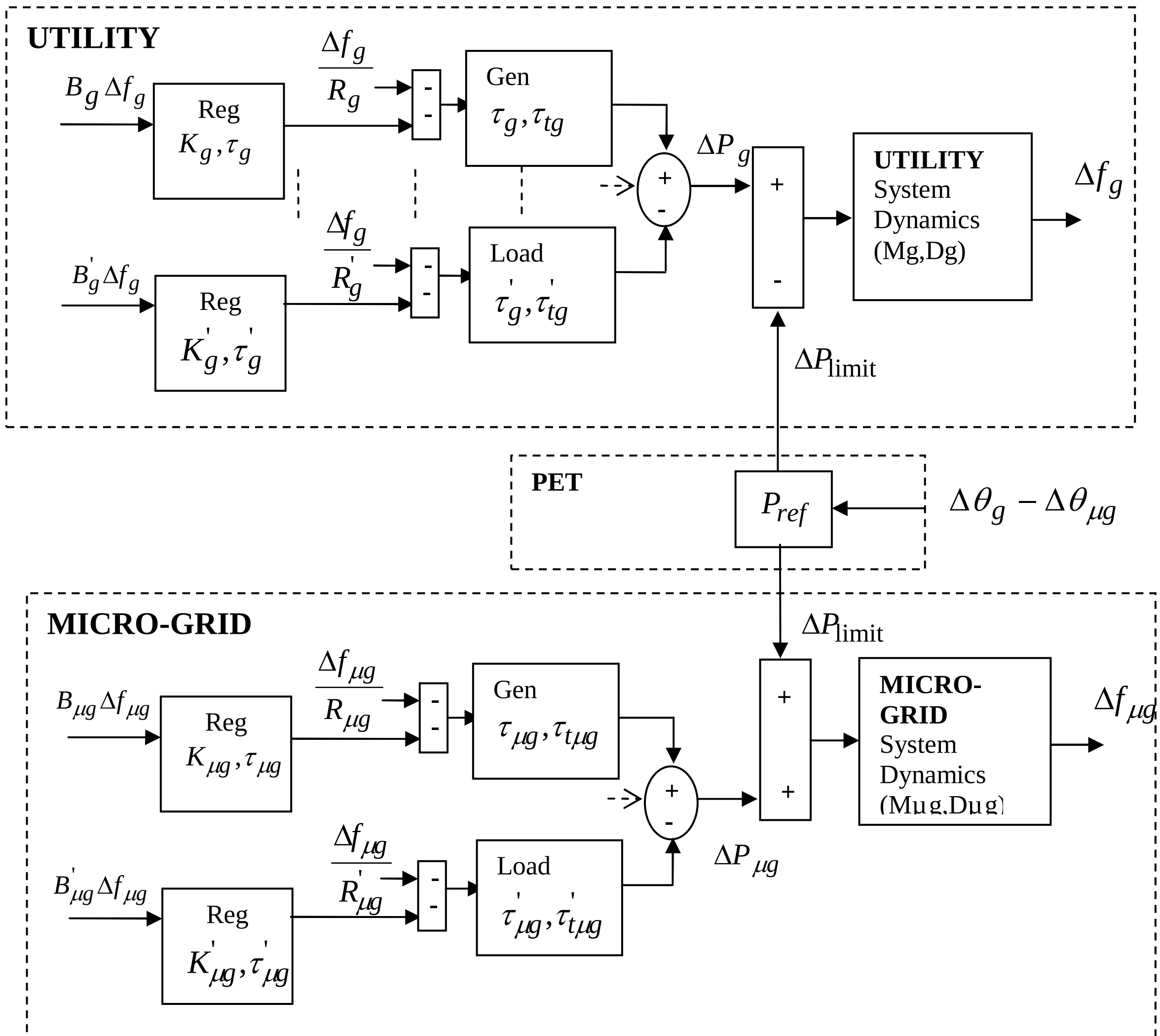

Figure 4-10 Micro-grid and Utility as two interconnected AC systems

The utility grid dynamics are determined from the equivalent generators and loads of the system while the micro-grid dynamics are different than those of the main grid. The PET connects the systems and provides bi-directional power flow between the two sytems ensuring that the sytems remain stable at steady state. The grid frequency f_g and the micro-grid frequency $f_{\mu g}$ are both regulated and the PET allows participation of the micro-grid in regulating grid frequency. The system is analysed with change in its parameters from pervious conditions. Hence a positive $\Delta P_{l\text{imit}}$ suggests that power is supplied to the micro-grid by the utility while a negative $\Delta P_{l\text{imit}}$ suggests power being fed to the utility.

4.4 Chapter summary

The micro-grid components are defined for system level analysis. The system level modeling is designed for n number of components. The primary and supplementary controls for the system are also defined. A detailed methodology of analysis for a micro-grid system is established with respect to the PET explained in chapter 3. A simplified modelling of the micro-grid components is established to simulate a system level design in order to verify the claims of the PET.

Chapter 5

Case-study

Micro-grids are commonly defined in terms of their structure. The major components of a micro-grid are the DERs and the associated loads. The micro-grids are designed to operate semi-independently and are usually connected to the main power grid. Often for reliability, cost-effective policy or other objectives, the micro-grids are expected to island and operate autonomously and the DERs within the micro-grid are expected to supply to the critical demand. Energy balance of the system is must and is maintained by dispatch of generation and non-critical loads, if controllable can be curtailed during energy shortfall or high costs. While connected, the micro-grids usually purchase energy or other ancillary services from the power grid and at times also sell power back to the grid. The PET claims to fulfill all the above objectives for the micro-grid and also allow the utilities define the limit on the bi-directional active power flow between the micro-grid and the main power grid.

To better understand the claims of the PET and understand the system level performance, the decentralized control strategy as explained in chapter 4 is explored to specific case study for a micro-grid [55] consisting of:

- **DERs:** microturbines (3ø, 30kW; 3ø, 25 kW), wind turbine (3ø, 15 kW) and PV array (3ø, 15kW).
- **Loads:** Residential load (3ø, 1ø, 52kVA), Commercial controllable load (3ø, 75kVA), single residential load (3ø, 15kVA), critical load, e.g. hospital (3ø, 1ø, 20kVA).

The chapter analysis the claims of the PET and supports the system level design established before. Two cases are considered, starting with a more simplified micro-grid structure consisting of only two DG units and loads considered of the two kinds: controllable and non-controllable. The DERs driven by both renewable as well as non-renewable sources are considered. The renewable microsources are expected to provide optimal power at all times. The variation in their generation is also considered to analyze the system performance. A more complex micro-grid is considered in case 2. Further case 3 verifies the participation of micro-grid components in frequency regulation of the main grid on account of the PET.

5.1 Case 1: Simplified micro-grid structure with minimum complexity

The simplified micro-grid structure assists in understanding the prime importance of a smart micro-grid with PET at the PCC. For a simplified micro-grid system [55] as shown in figure 5-1, one of the DG unit is a microturbine (3ø, 30kW) while other is a non-dispatchable wind turbine (3ø, 15 kW). The system supplies to a residential load (3ø, 1ø, 52kVA) and a commercial controllable load (3ø, 75kVA). The DG units are expected to have AGC while the loads have ALC to provide supplementary controls. The values of the parameters involved are given in table 3. The PET at the PCC of the micro-grid limits the grid power as supplied to the micro-grid. It also steps down the voltage (20kV to 400V) as well as provides isolation. In an event of load disturbance or limited grid power, the DG units and the commercial load can sense the drop in grid frequency ($\Delta\omega$) locally and respond to meet with the energy requirements. The system is modeled in MATLAB/Simulink. Appendix B gives the detail Simulink models.

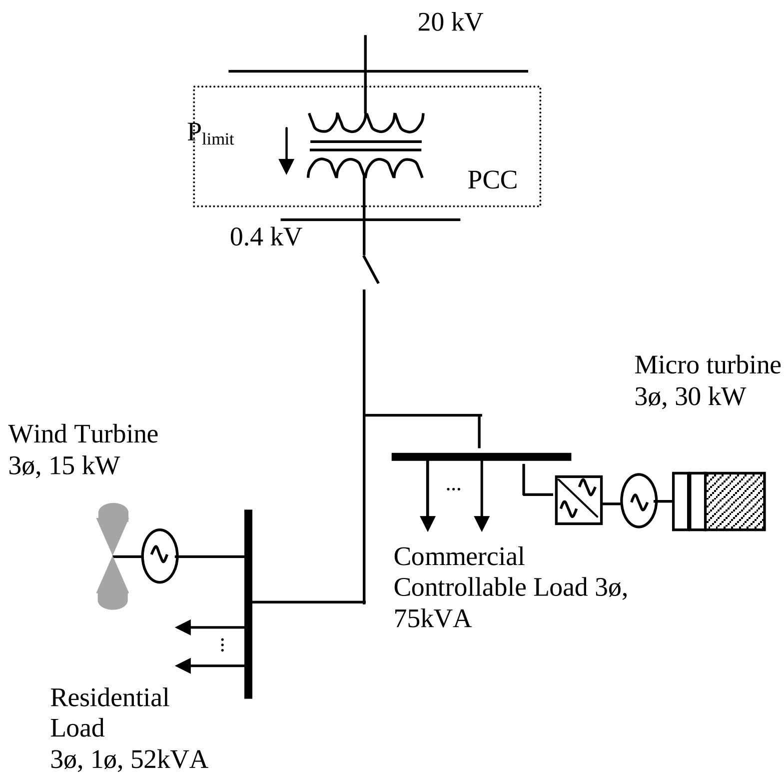

Figure 5-1 Simplified micro-grid structure

The microturbines are assumed to be non-reheat type and have two time constants associated with its governor and speed control mechanism. The time constant for the controllable load is assumed to be smaller as compared to the microturbine. The percentile change in grid power is experienced at time step t=0 and the system is assumed to have a load disturbance of 0.5 percentile at the same instant. With these parameters, case 1 is further analyzed for several scenarios to get a better understanding of the control at the PCC achieved by the PET, over the system components.

Table 4 Micro-grid component parameters case 1

Micro-grid Components	**Model Parameters**
Microturbine ΔP_{m1}	R_1=0.167 $\tau_{g1} = 0.26$ $\tau_{s1} = 0.26$
Wind-turbine ΔP_{m2}	0
Commercial ΔP_{LC}	R_1=0.1 $\tau_{g1L} = 1$
Residential ΔP_L	0.5 percentile
Grid Power ΔP_{limit}	-1 percentile

5.1.1 Without supplementary control

With the parameters given in table 1 for case 1, the system is analyzed with no AGC or ALC associated with the DG units or the controllable loads. The controllable load is basically constant and its consumption is not controlled. Figure 5-2 and 5-3 give the simulation results for the system. It can be seen that with no AGC or ALC in the system, the frequency of the system drops and does not regain its initial value. The generation from the microturbine has to be increased to match the load disturbance as well as restricted grid supply. Figure 5-2 shows the variation in system frequency upon step load disturbance as well as with grid power restricted at the same instant and the system now operates at deviated frequency. Also it is seen that the microturbine does increase its generation but has not fully matched the load.

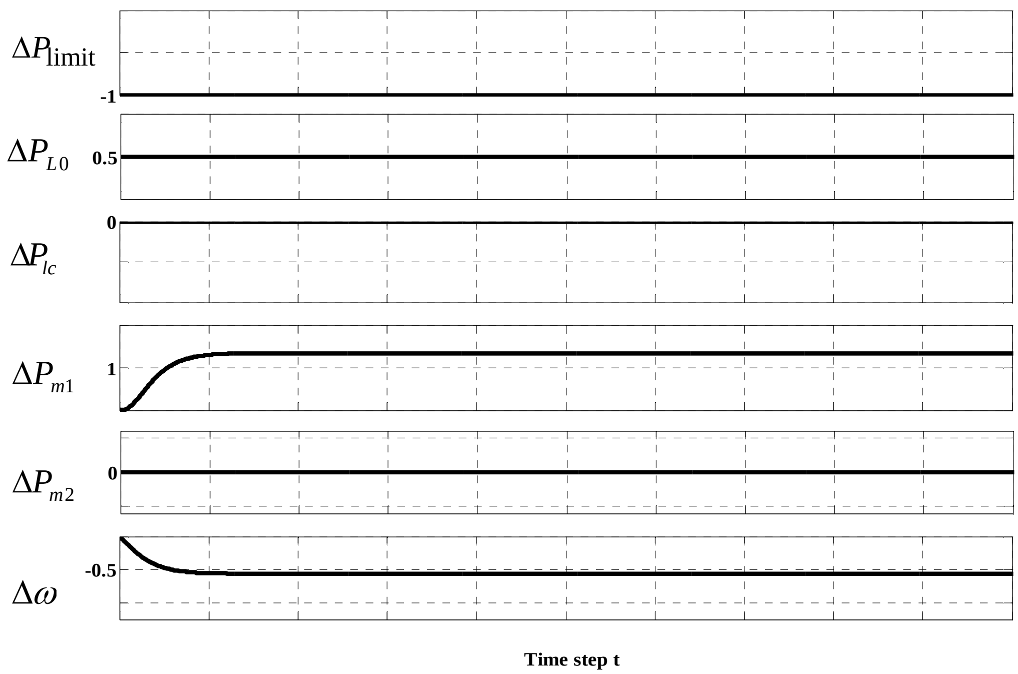

Figure 5-2 Power flow control for case 1.1

Figure 5-3 shows the overall system performance. The load demand and generation are not matched without any AGC in the system. At time step t=0 the overall system demand has increased and with that the generation has also increased.

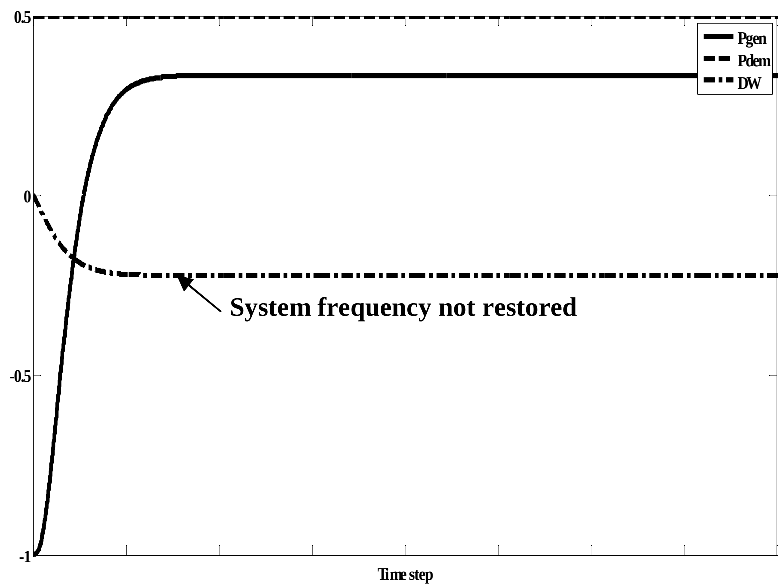

Figure 5-3 Steady-state system performance for case 1.1

5.1.2 Microturbine with AGC

To regulate the frequency droop, AGC is considered for the DG unit (microturbine). The controllable load is still not considered and hence variation in consumption in response to frequency drop is zero. Once again a step load disturbance is given at time step t=0 and at the same time the utility grid power is restricted. Figure 5-4 shows the corresponding results. Here the DG unit matches the load demand and hence the frequency of the system is regulated. Note that with no ALC present the DG unit solely matches the load demand. This may not always be economically feasible. Figure 5-5 shows the system performance under these conditions and that the load demand and supply match after a certain period of time. Also the system frequency is regained, thus ensuring system stability. Figure 5-5 shows the overall system performance where $\Delta\omega$ is zero at steady state and the energy balance is attained in the system.

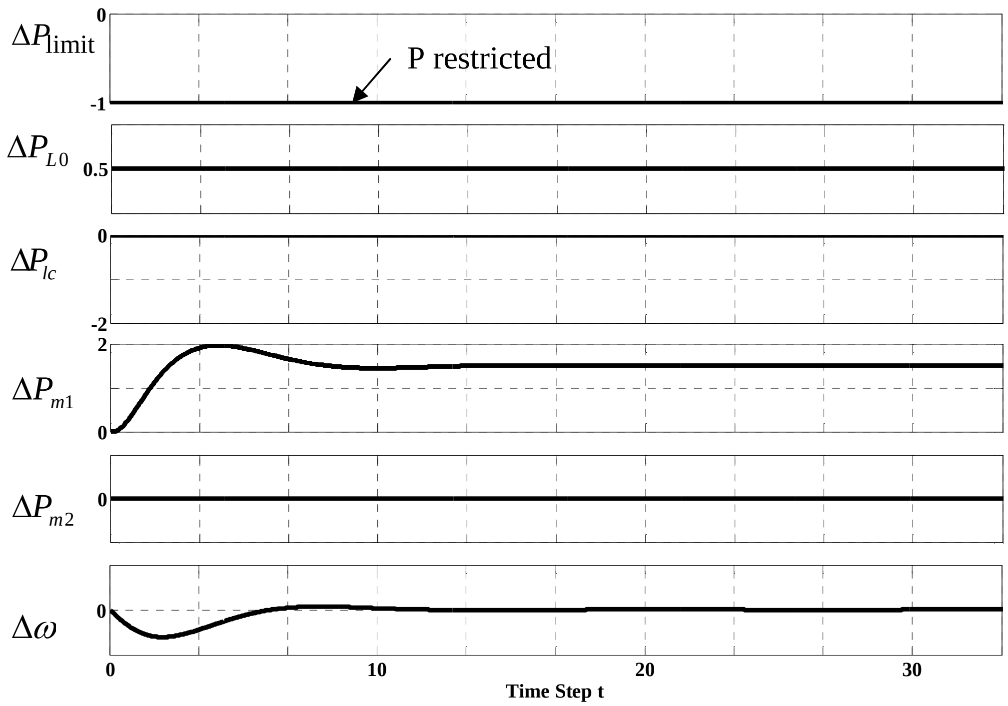

Figure 5-4 Power flow control for case 1.2

5.1.3 Controllable load with ALC

The entire system is studied with AGC and ALC in the system components. With the presence of ALC the load demand is distributed between the controllable load and the DG unit, thus ensuring a more economically feasible control of frequency. The system frequency is also regained As seen in figure 5-6 the DG unit increases its generation but the overall system generation has reduced due to the restricted grid power. Corresponding to that the overall system demand has also been reduced to attain demand-supply balance.

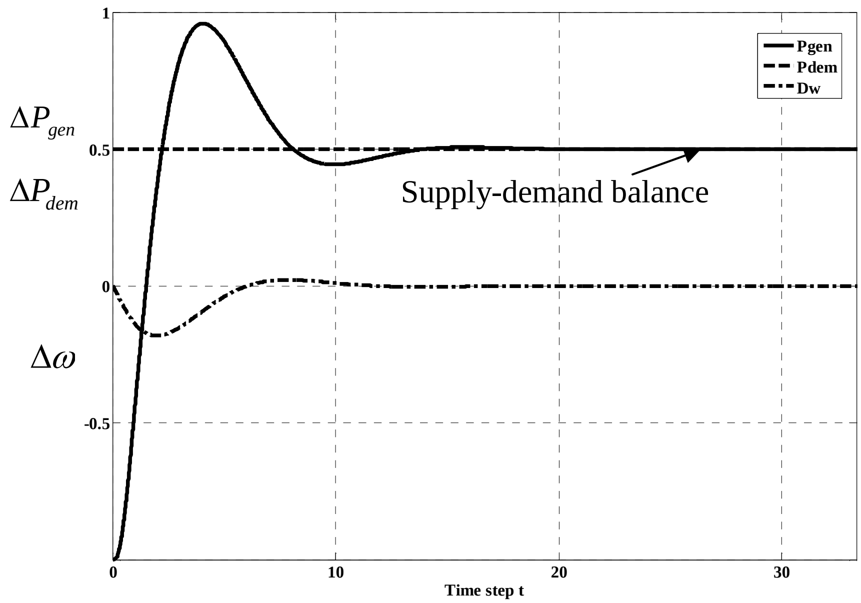

Figure 5-5 Steady-state system performance for case 1.2

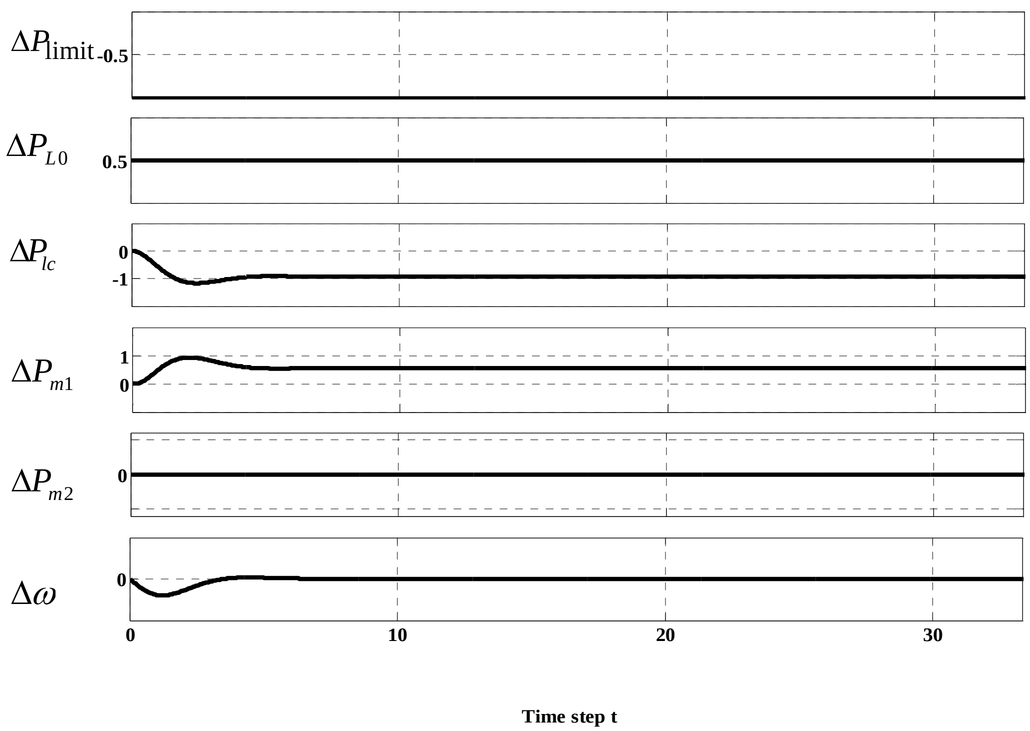

Figure 5-6 Power flow control for case 1.3

The overall system performance considering both ALC and AGC in the micro-grid components is shown in figure 5-7.

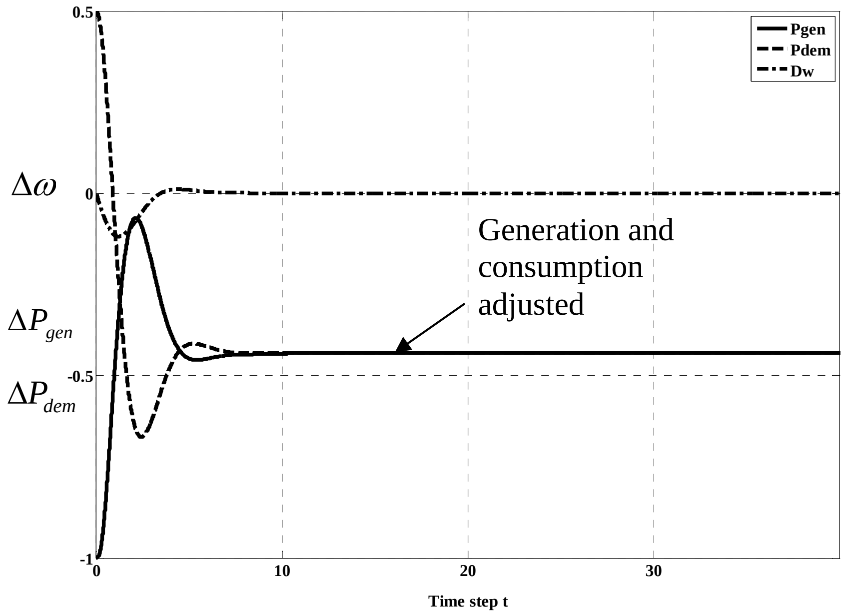

Figure 5-7 Steady-state system performance for case 1.3

5.1.4 Step load disturbance and grid power restriction

A more dynamic state of operation is considered where the grid power is first restricted at time step t=0 and later the grid power is regained to its original value. A step load disturbance occurs later to that and the system components respond accordingly. Upon restricted rid power initially the load reduces its consumption and the generation is increased. When power is regained at time step t=30, all the components operate at initial conditions until a load disturbance occurs at time step t=50. Figure 5-8 shows the response of the components to any frequency variations and also each time the frequency is regained. Figure 5-9 shows the system performance where at both the time steps when there is a drop in the frequency, the load and demand are matched.

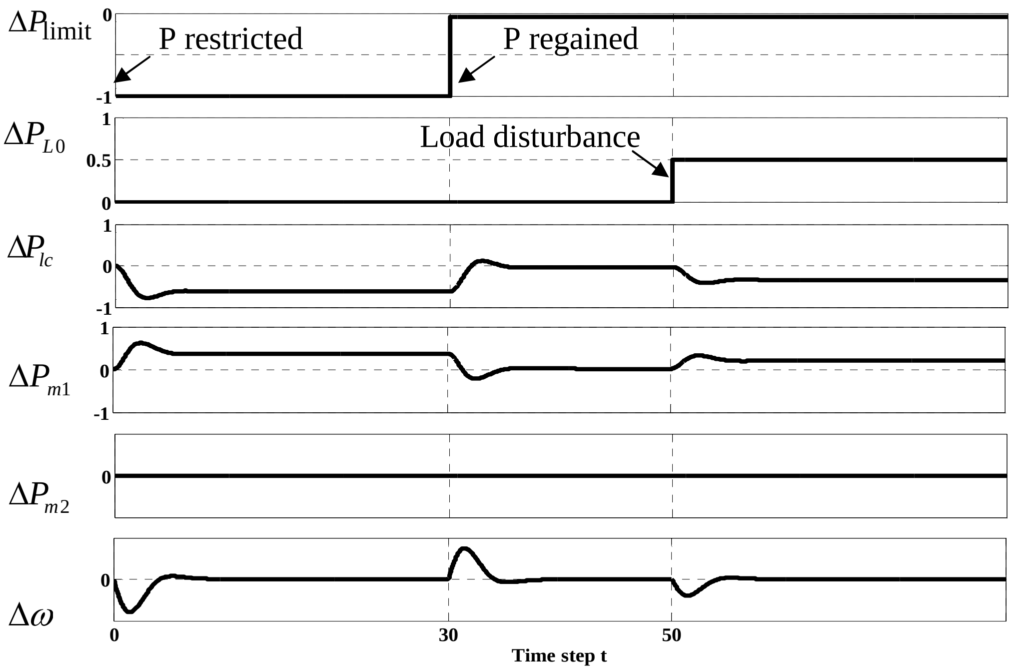

Figure 5-8 Power flow control for case 1.4

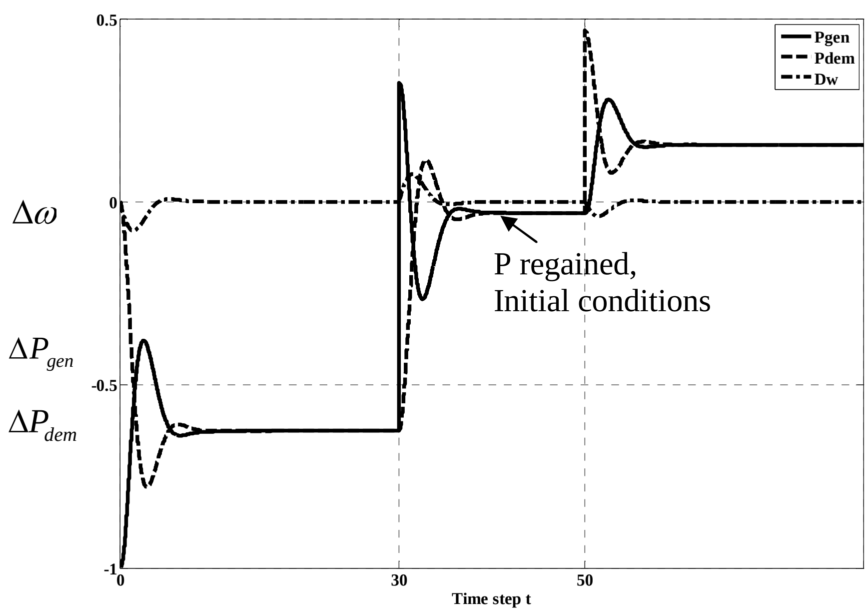

Figure 5-9 Steady-state system performance for case 1.4

5.2 Case 2: Extended micro-grid structure.

The micro-grid of case 1 is extended with more components and thus increasing the complexity of its operation. Here there are two dispatchable and two non-dispatchable DG units. The microturbines are expected to vary the generation in order to achieve energy balance. The wind turbine and the PV generator are assumed to operate at optimal operating points producing maximum allowable power. This system is similar to the case one except that both microturbines have different generating capacity. Some portion of the consumption is also reduced due to the controllable loads. Table 5 gives the parameters involved in the simulation.

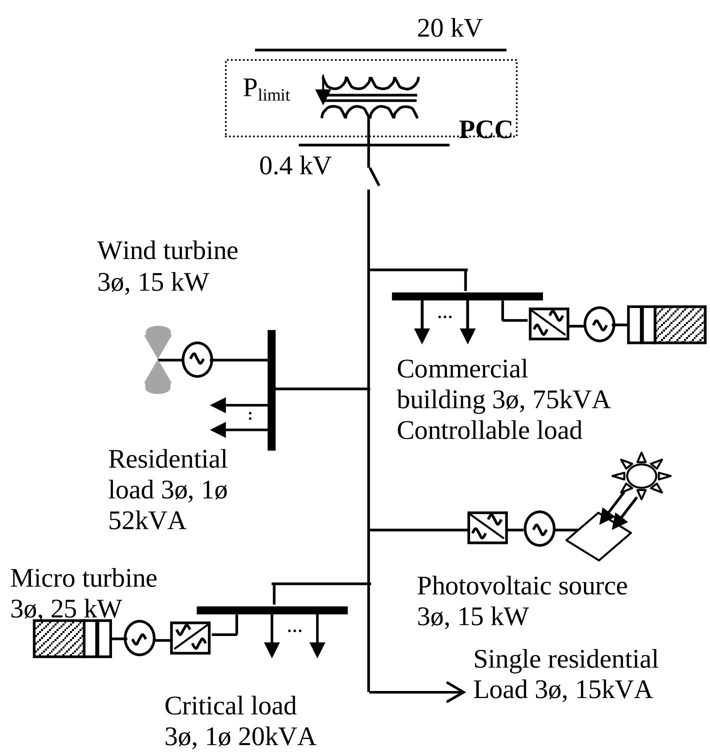

Figure 5- 10 Micro-grid structure for case-2

Table 5 Micro-grid component parameters case 2

Micro-grid Components	**Model Parameters**
Microturbine ΔP_{m1}	R_1=0.167 $\boldsymbol{\tau_{g1} = 0.26}$ $\boldsymbol{\tau_{s1} = 0.26}$
Wind-turbine ΔP_{m2}	0
Micro turbine ΔP_{m3}	R_1=0.3 $\boldsymbol{\tau_{g3} = 0.4}$ $\boldsymbol{\tau_{s3} = 0.4}$
PV Array ΔP_{m4}	0
Commercial ΔP_{LC}	R_1=0.1 $\tau_{g1L} = 1$
Residential ΔP_L	0.5
Grid Power $\Delta P_{\lim it}$	-1

5.2.1 Step load disturbance and restricted grid power

Figure 5-11 shows a simple case of reduction in utility power and load disturbance. With the non-dispatchable resources not participating in controlling their generation, the controllable loads reduce their consumption while the microturbines increase their generation. Figure 5-12 shows the overall system performance and system frequency restoration.

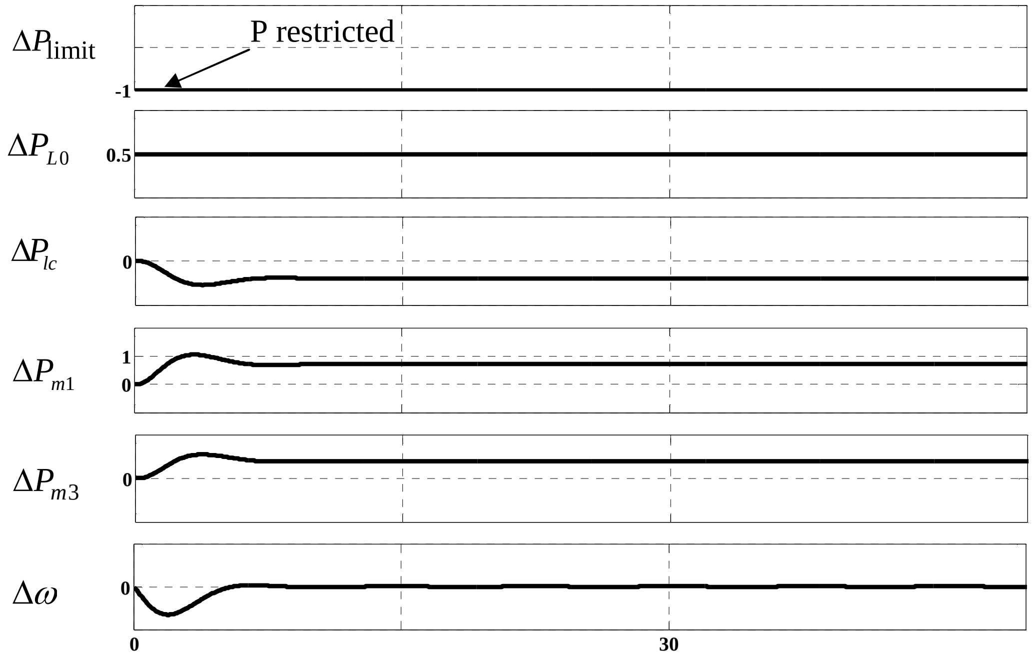

Figure 5-11 Power flow control for case 2.1

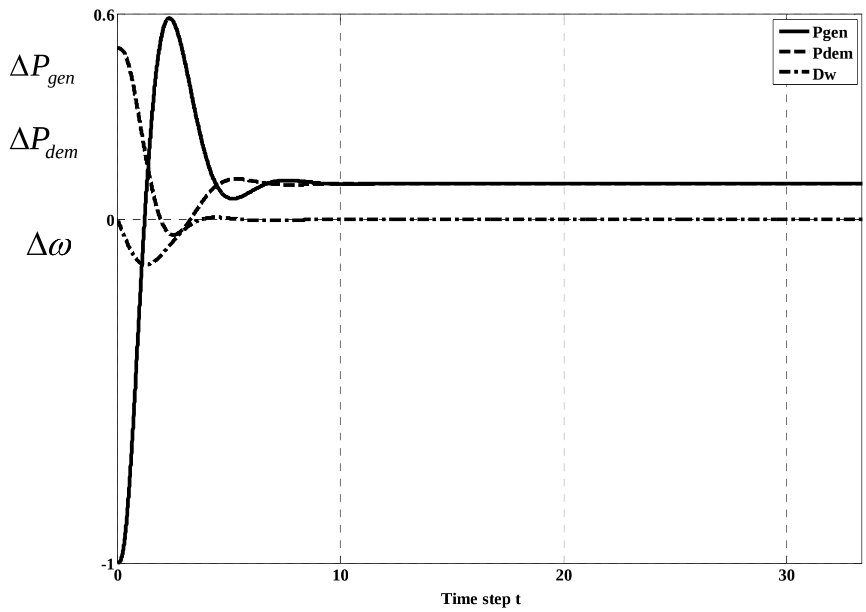

Figure 5-12 Steady-state performance for case 2.2

5.2.2 Step load disturbance and restricted grid power with faulty DG

Another case is considered where all the four DG units are considered. The non-dispatchable units are assumed to provide some variations in generated power and have a limit up to which they may increase their generation. At time step t=0 the grid power is restricted. The DG units provide the required increase in generation while the controllable loads also participate. At time step t=15 the load disturbance further disrupts the supply-demand balance. As a result of which the controllable load reduces its consumption to an acceptable maximum limit.

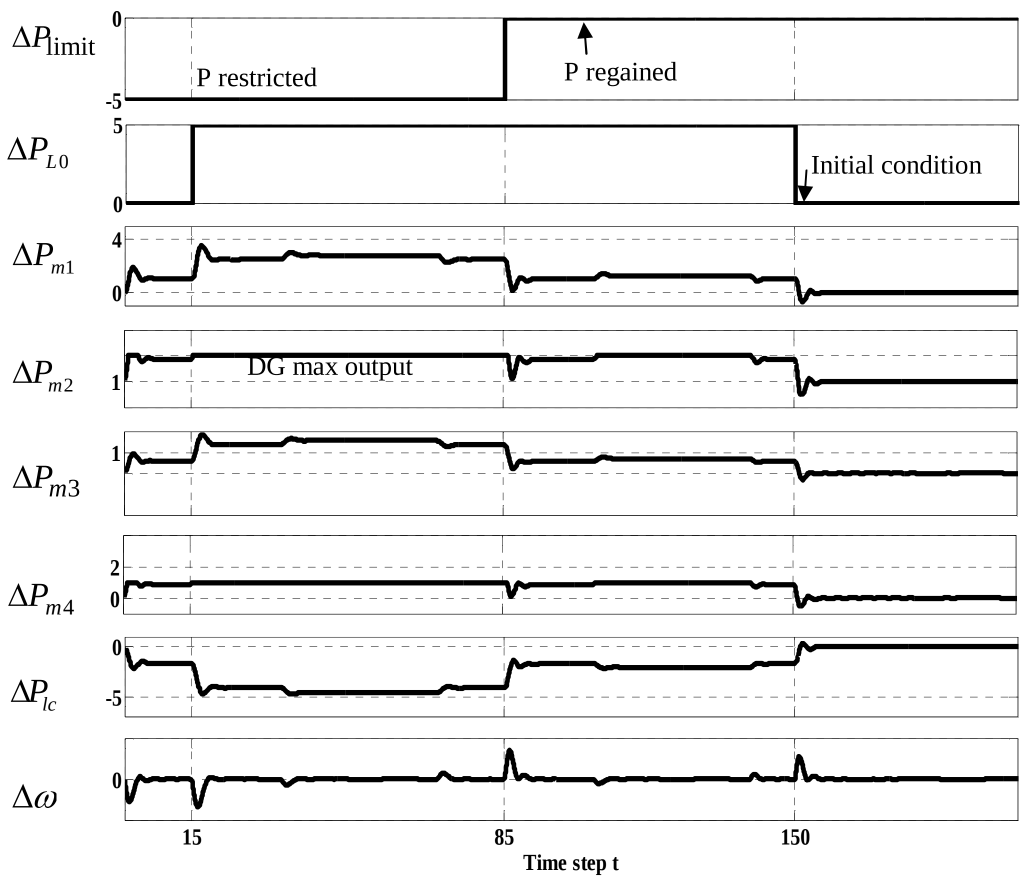

Figure 5-13 Power flow control case 2.2

At time step t=70 the DG unit 4 (PV Array) experiences a fault and not participating in energy supply any further. This causes the remaining generators to share load. With the DG unit 2 (wind turbine) at the maximum possible variation, the microturbines are required to increase their generation as the controllable load further reduces its consumption. At time step t=85 the grid power is restored and at time step t=100 the load demand of the system attains the initial operating conditions. Figure 5.14 shows the overall system performance and energy balance for the above variations. When initial conditions are reached the generation and consumption are adjusted to their previous values so that the system frequency is also restored.

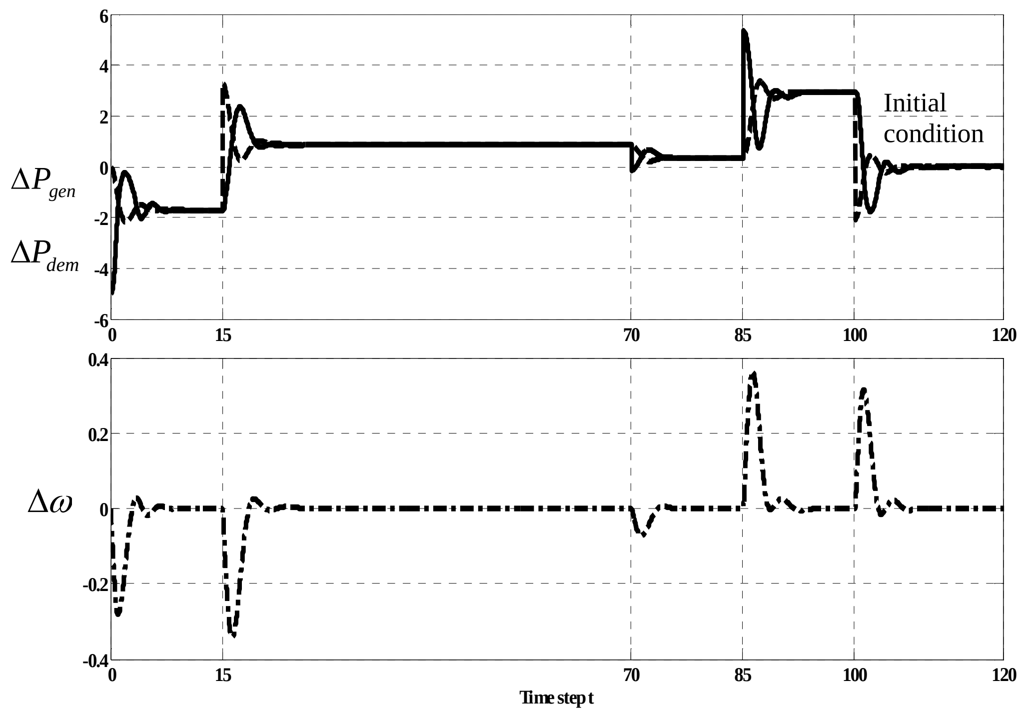

Figure 5-14 Steady-state system performance case 2.2

5.3 Case 3: Frequency restoration of main grid

Consider a case where the main grid is connected to the micro-grid with a regular distribution transformer. In a case where the grid experiences load disturbance, the generation and consumption within the main grid will try to adjust in order to restore the system frequency. There is no load disturbance in the micro-grid at that point. Without a PET there may be certain amount of power flowing from the main grid to the micro-grid resulting in no participation from the micro-grid components in frequency restoration of the main grid. Since the power is being transferred to the micro-grid, its components adjust within to restore the micro-grid frequency.

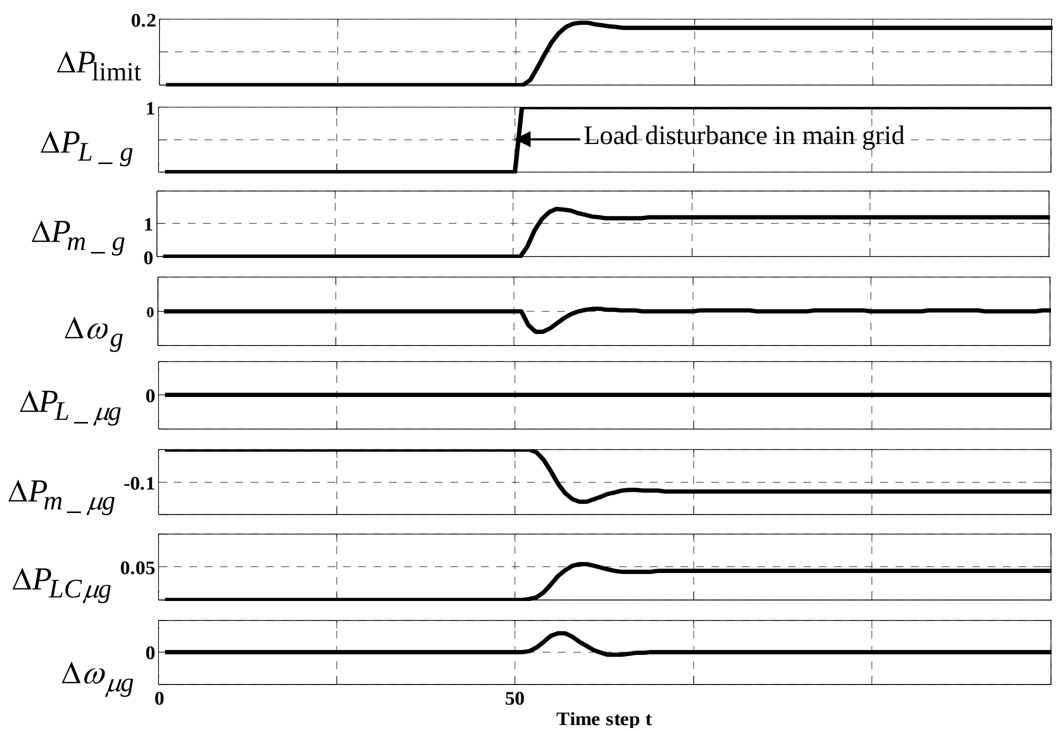

Figure 5-15 Frequency restoration in main grid without PET.

Unlike to the previous case, with a PET at the PCC and similar load disturbances now the micro-grid components are allowed to participate in the overall system frequency restoration. As can be seen in figure 5-16 the generators and controllable loads within the micro-grid adjust the supply and demand to some extent and thus participate in main grid frequency regulation. This is another advantage of the PET which may extend its application in establishing market strategies useful both to the micro-grid as well as the utilities. It also ensures optimal use of renewable resources and economical operation of all the DERs that constitute the system.

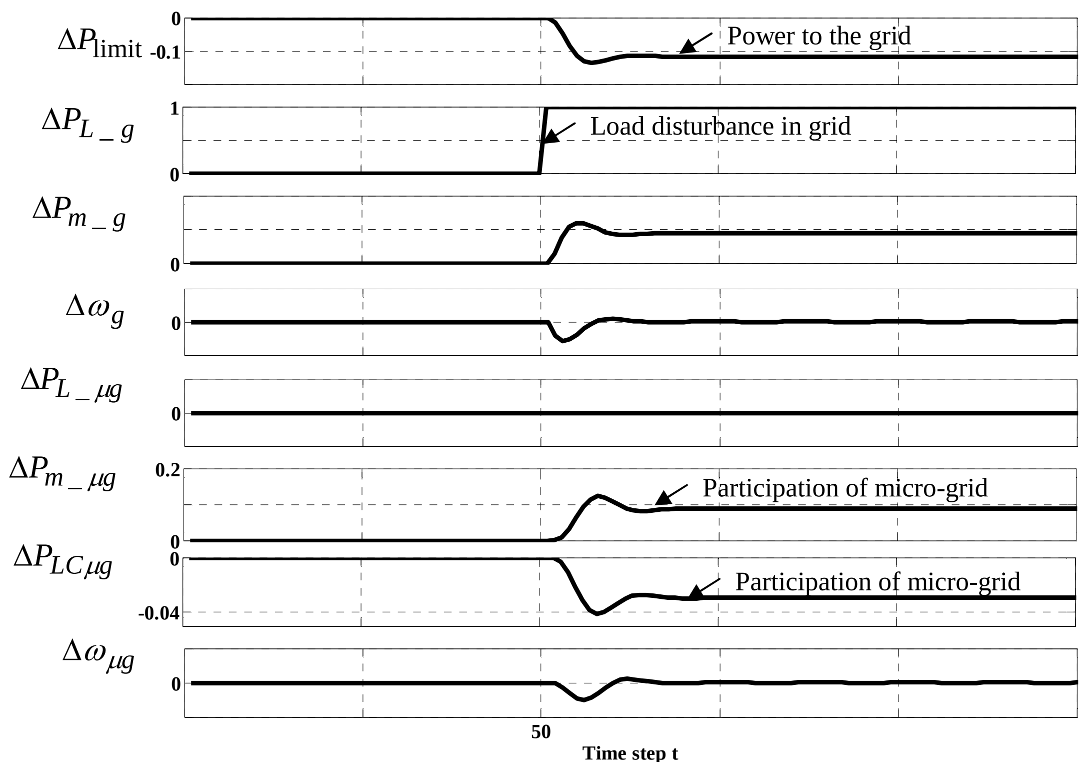

Figure 5-16 Frequency restoration of main grid with a PET.

Figure 5-17 extends the case with a load disturbance that may occur in the micro-grid prior to any disturbances in the main grid. It is essential that the micro-grid components respond to any disturbance that may occur within. Without a PET, the difference in supply to demand is made available at the PCC. As seen in figure 5-17 the generation and consumption within the micro-grid is adjusted and the ΔP_{limit} is varied in response to the supply-demand imbalance. At a later instant with a load disturbance within the main grid the microsources no longer participate in frequency restoration of the main grid.

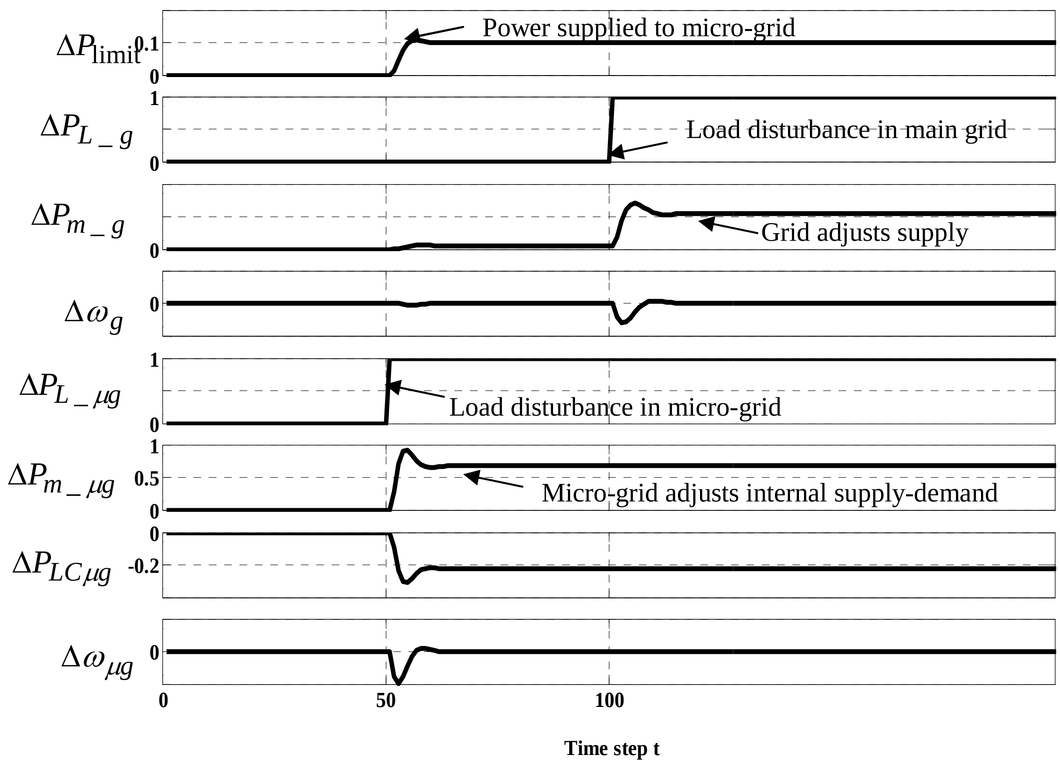

Figure 5-17 Frequency restoration of main grid without PET

With a PET in similar case as described above, initially when the micro-grid experiences load disturbance there will be active power flow from the main grid to the micro-grid. At a later instant when the main grid experiences load disturbance, the two AC systems act as two interconnected power systems and the microsources together with the components of the interconnected system restore the frequency of the main grid.

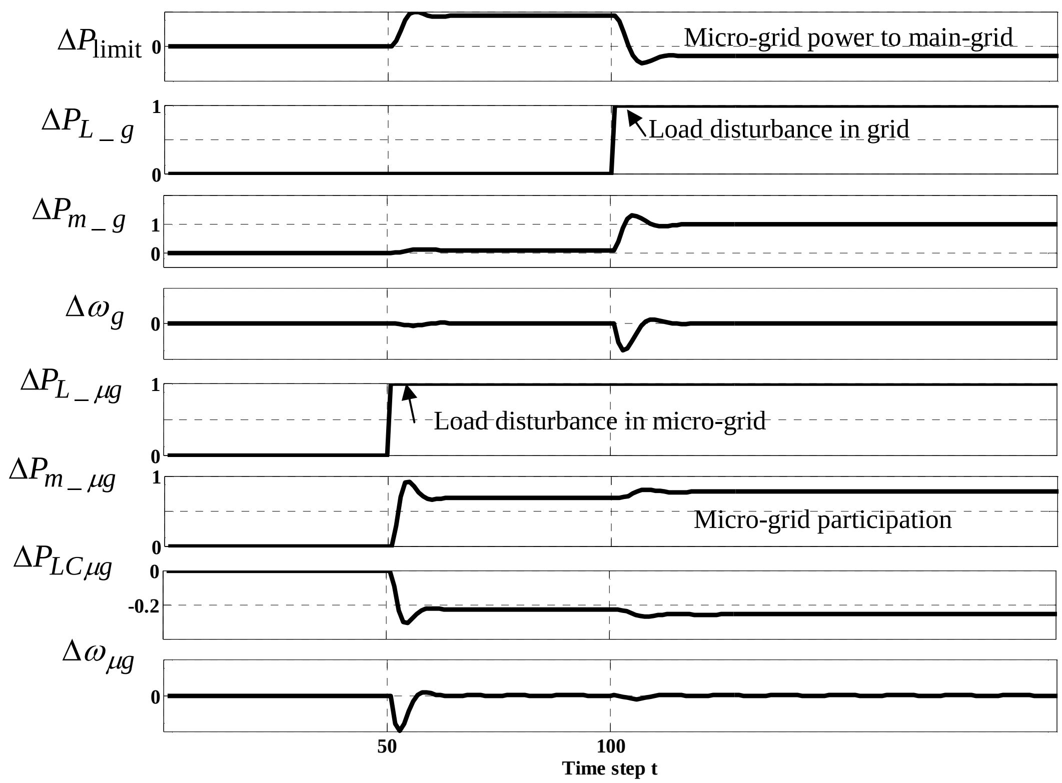

Figure 5-18 Micro-grid participation in frequency regulation of main grid

From the above case study it can be verified that the PET has another advantage of allowing the DER units of the micro-grid to participate in frequency regulation of the main grid to some extent. This provides an extra degree of freedom in a certain market strategy and possible deregulation.

Note: Portion of this chapter is reproduced from my IEEE publications [24],[54-55]

Chapter 6

Conclusion

The consistent increase in the penetration of the DERs has recently generated significant interest in the controls and communications involved. Micro-grids have been extensively researched to efficiently integrate DER units into low voltage electricity system and for their optimal utilization. Smart power and energy management policy are prime challenge for micro-grids. The interconnection of DERs has increased concerns in regards to the adverse impacts on the power quality of the main grid especially due to the power fluctuations caused by renewable resources. Hence the controls and interface of micro-grids with the main power grid play a vital role in successful and optimal operation of the entire power system. A PET, on the other hand has also been extensively researched for its size and weight advantages over conventional transformer. The thesis extended the application of the PET for bi-directional power flow control between the utility and a micro-grid. The need of proposing a novel strategy to provide enhance power management to smart micro-grids is addressed. The claims of the PET as established and substantiated by simulation results and case study.

In chapter 3, a PET is proposed for its application in power distribution system. The chapter also explains operation of a three phase to single phase matrix converter that provides high frequency operation of the PET. Bi-directional power flow is achieved between the two three phase AC systems. The PET, unlike a conventional line frequency transformer, can restrict the power flow between the two AC systems at its primary and secondary. With equivalent AC microsource on the secondary, smooth transition from islanding to the grid-connected mode can be achieved. The active power limiter provides with an extra degree of freedom to both, the utility grid and the micro-grid, in possible deregulation and market strategy. Chapter 3 verified the several claims of a PET as applied to the micro-grid by simulation results of a complete PET schematic in MATLAB/Simulink.

Chapter 4 established a strategy for operational concepts of a micro-grid and its basic components were defined. The power management in a micro-grid is discussed. A fresh approach of decentralized control strategy of DER units and loads, that constitute a micro-grid, is proposed. The microsources and controllable loads utilized the change in system frequency to adjust their generation or consumption. When active power at the PCC increases beyond a pre-set limit the PET restricts the power flow from the utility grid. The resulting drop in grid frequency is sensed locally by the DG units and loads for dynamic active power flow control. The PET, by controlling the dynamic active power flow at the PCC, is indirectly controlling the generation and consumption within the micro-grid. Thus achieving a decentralized control of the micro-grid components and hence the grid frequency. The proposed power management for micro-grid is verified in chapter 5 by a case study of a complex micro-grid system.

The major benefits of the smart micro-grid as compared to a regular micro-grid, as achieved in the simulation results and case study from the previous chapters, are listed below:

1. In the grid connected mode of a ***regular micro-grid***, the DGs are controlled to supply a pre-set value of active power. Based on the load change, the difference of supply (active power generated by DGs) and demand (load active power) is supplied by the power system grid. In the event of a sudden load change in the micro-grid, the active power flow at the PCC can vary significantly which may be undesirable during the peak load demand from the power system grid. However, the active power command in the DGs can be controlled to make the power system grid less susceptible to the load fluctuations in the micro-grid.

   In a ***smart micro-grid***, with a PET at the PCC, the active power flow from the main grid can be dynamically controlled to a desired value determined by the utilities. This is verified by simulation results in section 3.5.2. The active power was dynamically reduced to 60% of the initial supply. The dynamic limit, as set by the utilities is achieved by the PET and the utilities do not need to communicate with the micro-grid components. In case-study, section 5.1 and 5.2 the response of micro-grid components to the grid power restriction is studied and is verified that the components do not require to communicate with the main grid.

2. In the smart micro-grid the PET achieves voltage regulation by control of reactive power. For any load disruptance the frequency at the PCC constantly varies. Also due to restriction in active power at the PCC by the PET the grid frequency may drop. This affects the voltage profile at the transformer primary. The PET modulation strategy allows control over reactive power which hence controls the voltage. This is verified in section 3.5.3 by simulation results.

3. In a regular ***micro-grid*** in grid connected mode, usually purchase energy or other ancillary services from the power grid and at times also sell power back to the grid. These decisions are usually made by a central micro-grid controller and depend on current economic strategies. Control of the active power for individual DG system based on the grid-frequency measured locally may not be possible, as the local grid-frequency is dominated by the power system grid in the grid-connected mode of operation.

   In a ***smart micro-grid*** the PET claims to fulfill the above objectives and also allow utilities to define a limit on the power supply back to the main grid from the micro-grid. This extends an extra degree of freedom under deregulation and market strategy and also ensures optimum use of renewable resources. This is substantiated in section 3.5.1, with simulation results in figures 3-11 and 3-12. Here bi-directional power flow is achieved by the modulation strategy of the PET and hence in control of the utilities.

4. In a regular ***micro-grid*** the frequency will not change enough to control the generation and consumption of the components. Control of the active power for

individual DG system, based on the grid-frequency measured locally, may not be possible as the local grid-frequency is dominated by the power system grid in the grid-connected mode of operation.

Decentralized control of the components is achieved in a ***smart micro-grid*** where frequency change upon grid power restriction adjusts the generation and consumption within the micro-grid. This is analyzed in case study section 5.1.4 where the controllable loads and the generators adjust their power consumption or generation in response to grid frequency variation. Section 5.2 further verifies that the micro-grid components do not require communicating internally and any fault in one component is reflected in the overall frequency variation.

5. A ***micro-grid*** is normally in grid-connected mode but often disconnects and operates autonomously in islanded mode. The transition between these two modes requires grid frequency synchronization and is required to be planned ahead of time for safe operation.

   In a ***smart micro-***grid the PET allows a smooth transition from islanding mode to grid-connected mode. As described in section 3.3 the output of the power converter in the PET is independent of input AC source frequency. Hence grid frequency synchronization is not required. If the micro-grid is operating at a frequency other than the utility, the main grid frequency is not affected. Thus the utility can totally disconnect the micro-grid by dynamically restricting the active power flow in case of any faults detected.

6. The utility grid frequency restoration is also essential with any load disruptance that may occur in the interconnected system. The PET allows participation of the micro-grid components in grid frequency stabilization. This claim is substantiated by case study analysis in section 5.3.

6.1 Future work

The proposed PET with its bi-directional power flow control ability may be applied at several levels of power distribution. With two of such PETs, a smart control strategy for economic operation of a power system could be achieved. As shown in figure 6.1 the PETs may choose to supply electricity to a critical load at energy shortfall conditions. The proposed decentralized control for micro-grids may assist in enhanced power distribution without totally shedding a load. This ensures optimal utilization of renewable resources. The critical load is supplied by the wind turbine under normal operating conditions. The PET direct active power to the several micro-grids connected downstream. The two PETs can now ensure reliable power to the critical load and utilize the renewable resources optimally. A simplified intelligent control between the two PETs could be established by regulating the power generation and consumption within the system in response to grid-frequency variations. Another approach to the PETs could be applied as a two winding transformer as shown in the schematic in figure 6-2. The PET can now control P_1 and P_2 individually and provided a constant P_T power from a system. Here P_1 can be power generated by a renewable resource and P_2 can be from a fuel based generator. The PET can now vary P_1 and P_2 and still provide a constant output power flow. A detailed power system analysis for the micro-grid with dynamic analysis of the DG units will propose many challenges to verify the PET claims. Advanced system level study may also constitute the fault analysis associated in the power system.

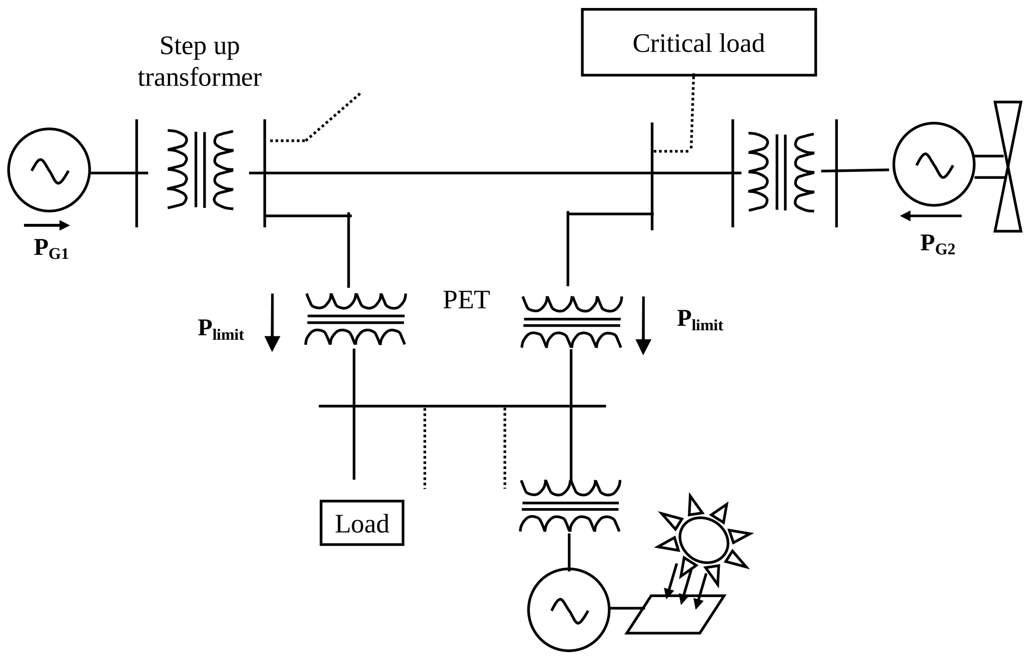

Figure 6-1 Two PETs operating in sync

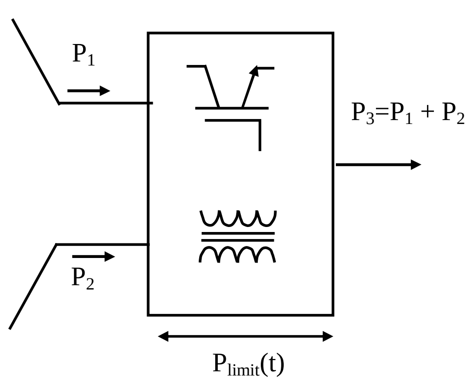

Figure 6-2 PET with a two winding transformer

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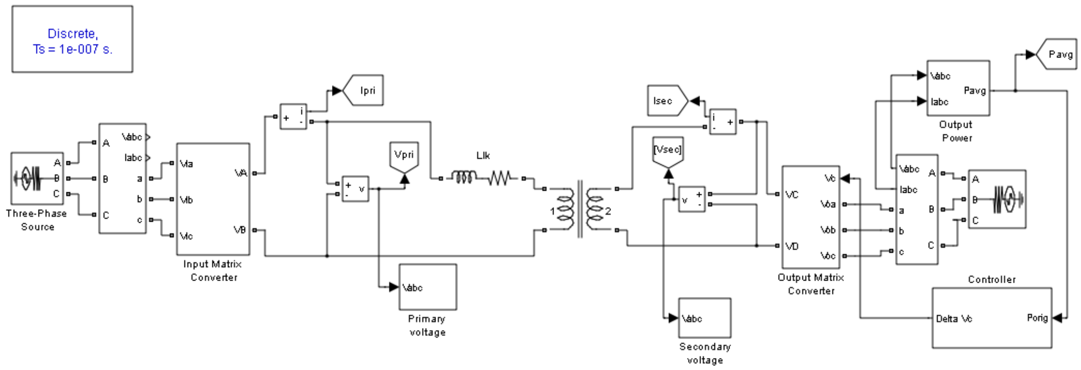
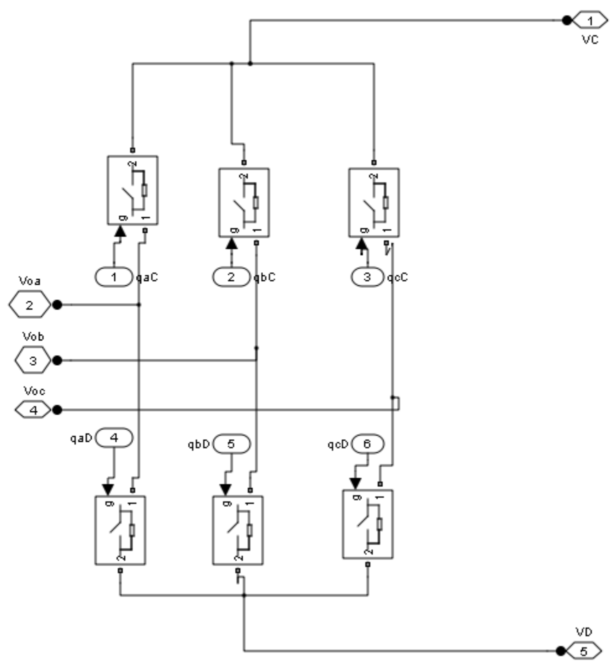
Appendix A

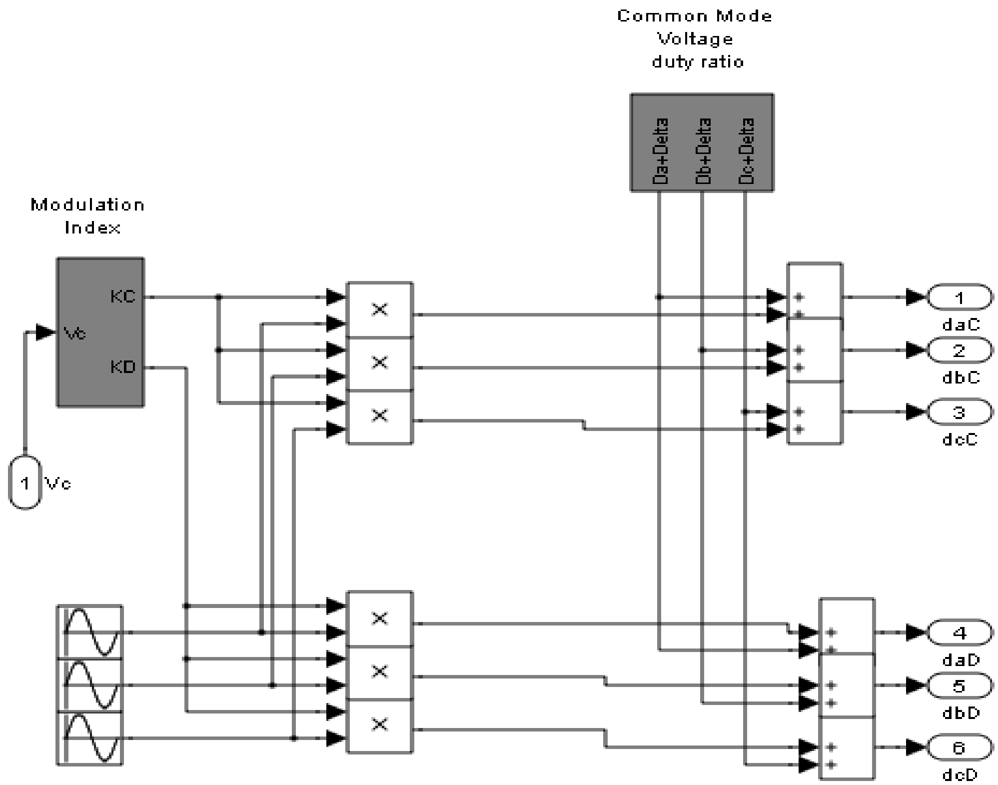
A.1 Power electronic transformer



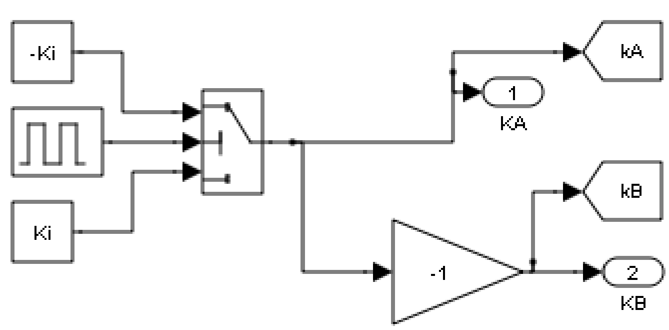
A.2 Matrix converter

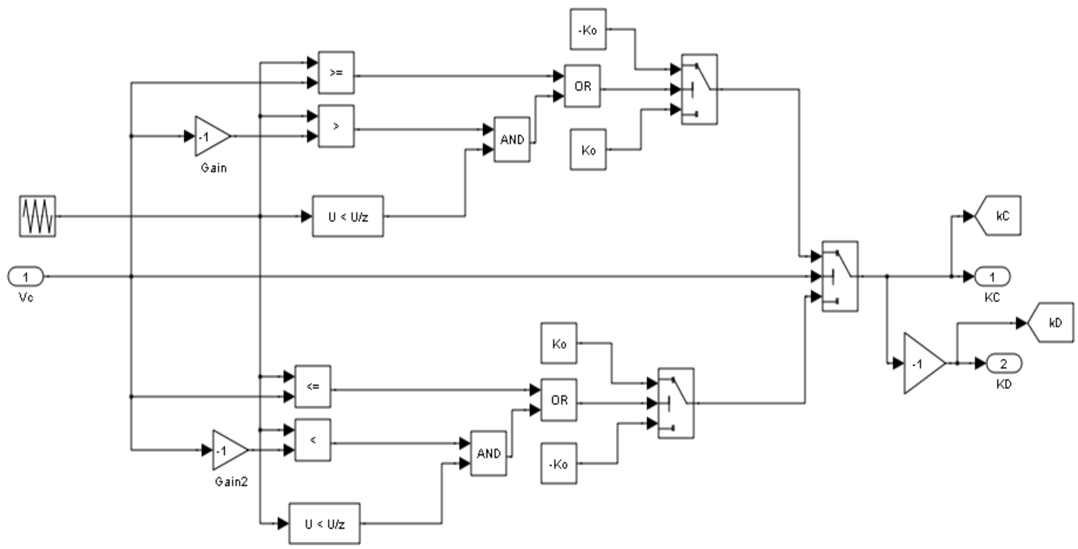


A.3 Matrix converter modulation

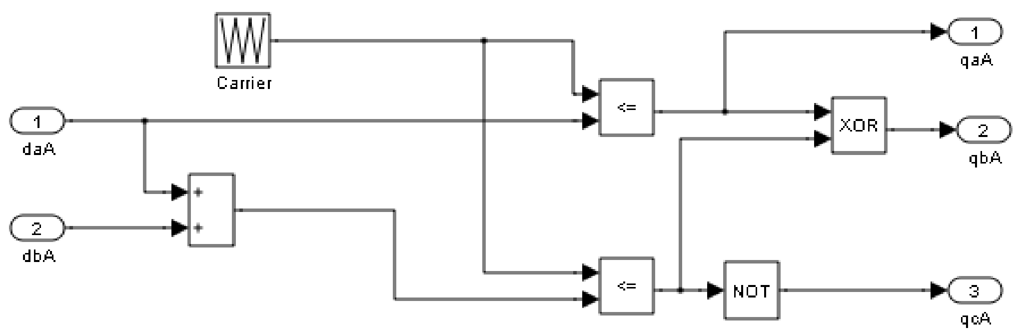


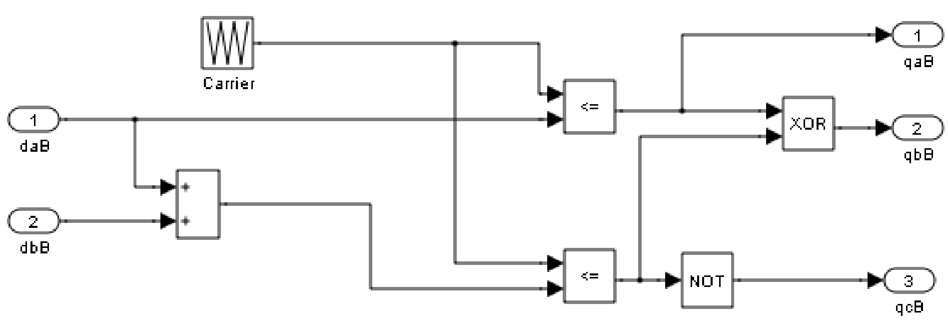
A.4 Modulation indices



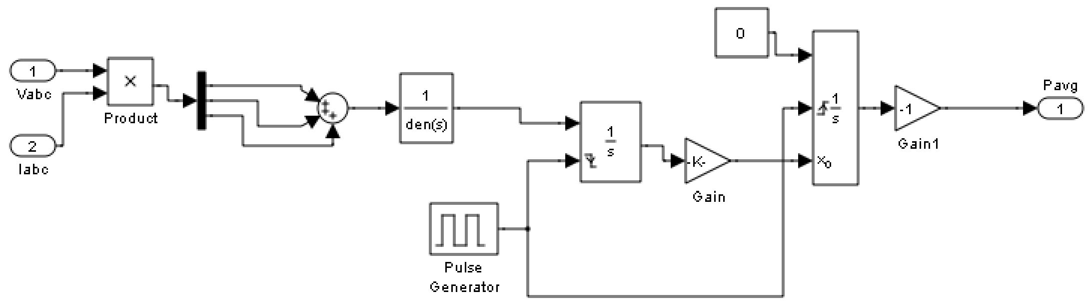


A.5 Switch states

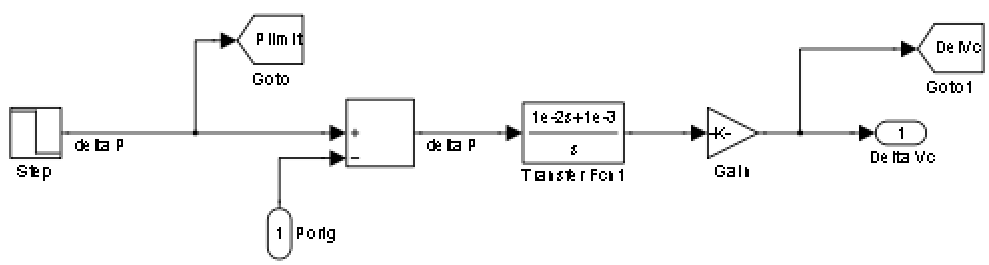




A.6 Active power measurement



A.7 Closed control loop



A.8 Simulation parameters

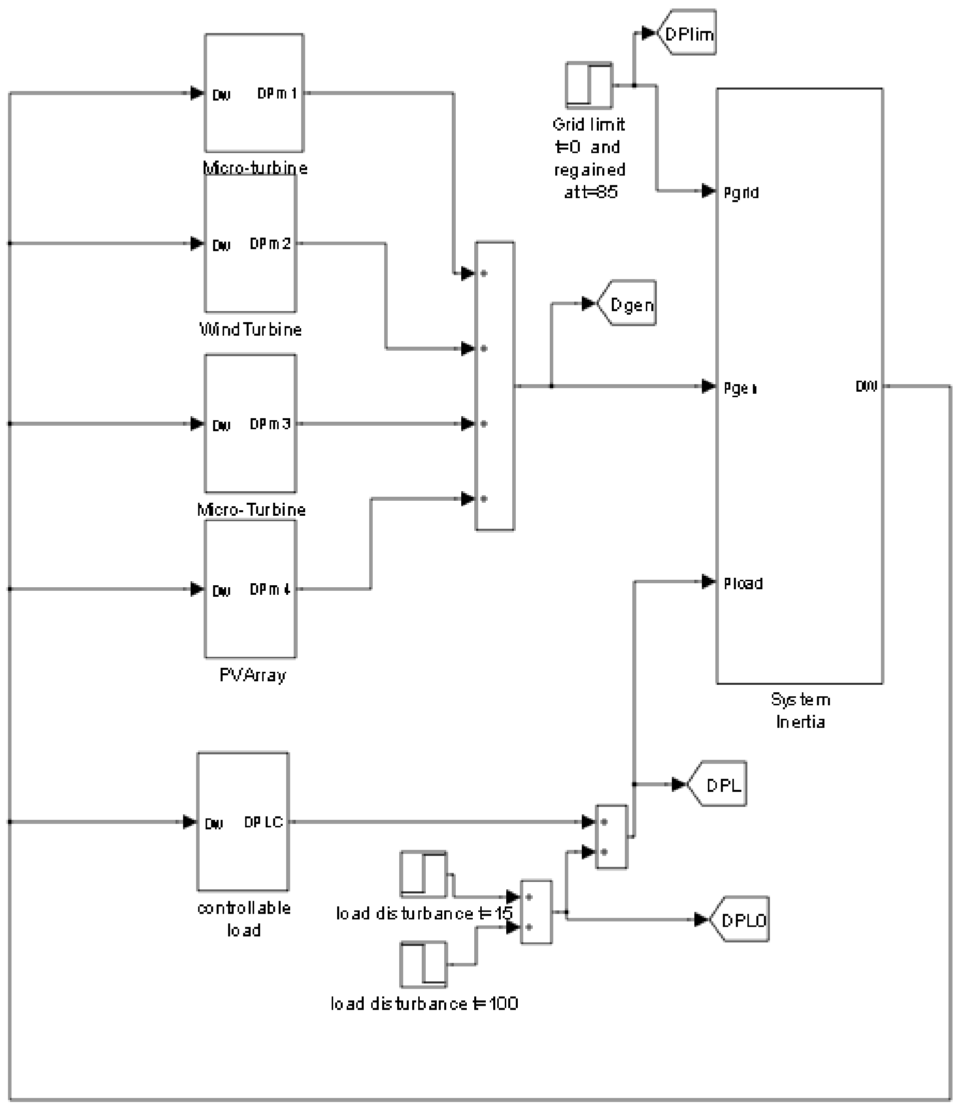
Table 6 Simulation parameters for PET

Input AC voltage	V_{in}	20kV (L-L, rms)
Input line frequency	f_i	60 Hz
Output voltage	V_{out}	400V (L-L, rms)
Output line frequency	f_o	60 Hz

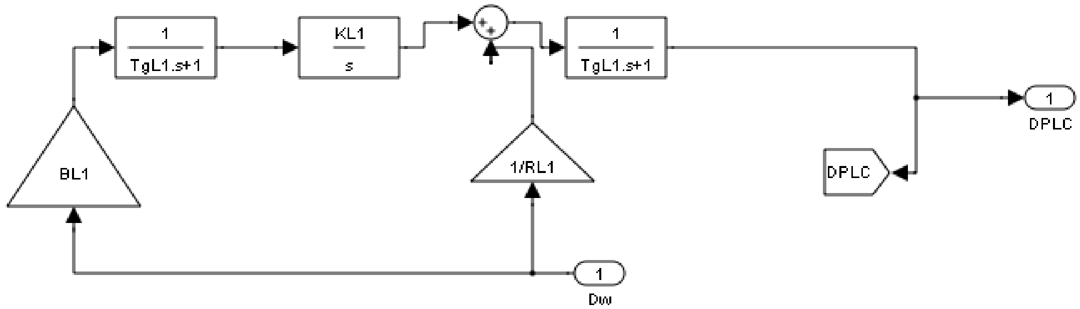
Switching frequency	f_s	10kHz
Modulation index	K_i=K_o	0.5
LC filter	L_f	2.5mH
	C_f	10µF
	R_f	0.01Ω
Transformer leakage reactance	L_{lk} R_{lk}	1mH 0.1Ω
IGBT on-state resistance	R_{on}	0.001 Ω
IGBT snubber resistance	R_s	0.1M Ω
IGBT snubber capacitance	C_s	Inf

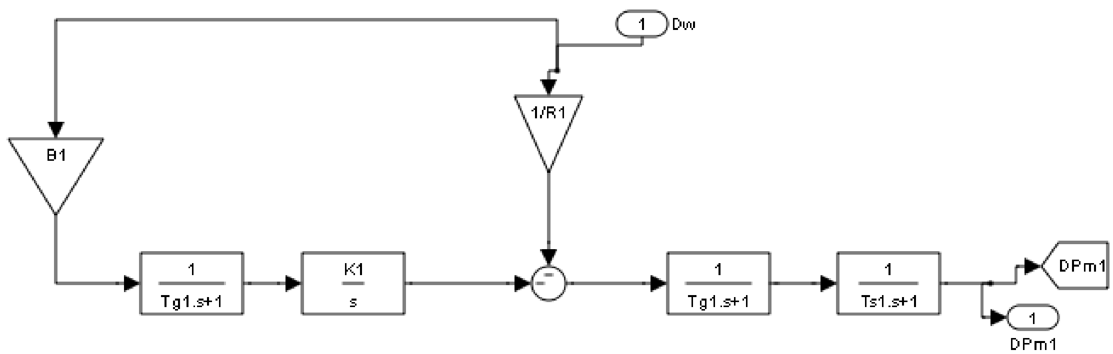
Appendix B

B.1 System level simulations



B.2 Generator and load model





B.3 Simulation Parameter

Table 7 Simulation parameters for system performance

Synchronous frequency	ω_{sync}	377 rad/s
Inertia Parameter(equivalent)	H	5.3
	$M = \frac{2H}{\omega_{sync}}$	
Damping factor (Generators & Loads)	D	
Regulation constant for microturbine 1	R1	0.167
Regulation constant for wind-turbine	R2	0.2

Regulation constant for microturbine 2	R3	0.3
Regulation constant for PV generator	R4	0.2
Regulation constant for controllable load	R_L1	0.1
Frequency controller gain for microturbine 1	K1	0.001 ω_{sync}
Frequency controller gain for wind-turbine	K2	0.001 ω_{sync}
Frequency controller gain for microturbine 2	K3	0.001 ω_{sync}
Frequency controller gain for PV generator	K4	0.001 ω_{sync}
Frequency controller gain for controllable load	K_L1	0.001 ω_{sync}
Turbine-governor time constant for microturbine 1	$\tau_{g1} = \tau_{t1}$	0.26
Turbine-governor time constant for wind-turbine	$\tau_{g2} = \tau_{t2}$	0.26
Turbine-governor time constant for microturbine 2	$\tau_{g3} = \tau_{t3}$	0.4
Turbine-governor time constant for PV generator	$\tau_{g4} = \tau_{t4}$	0.26
Turbine-governor time constant for controllable load	τ_{gL1}	1

B.4 Frequency regulation of main grid