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Distributed Model Predictive Control of Power Converters in Microsrids Under Different Modes of Operation

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DISTRIBUTED MODEL PREDICTIVE CONTROL OF POWER CONVERTERS IN MICROGRIDS UNDER DIFFERENT MODES OF OPERATION

by

Riyadh Toman Thahab Toman

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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Doctoral Committee:

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Ala Al-Fuqaha, Ph.D.
Microgrids consist of many distributed energy sources (DERs) and the overall system is viewed as a number of subsystems. In this work, a finite control set model predictive control is proposed to control power converters in both grid and island modes of operation of the microgrid. Each subsystem is assigned a local controller that relies on measurements of common coupling point (PCC) and/or terminal quantities to provide accurate regulation of current or voltage components. This meets the local objective of each subsystem and contributes to the global objective of the microgrid.

In the first part of the work, a microgrid system is considered with linear loading conditions: balanced and unbalanced portions. The control is based on decomposing voltage and current quantities into positive and negative sequence components by using synchronous reference frames. Components to be controlled are then extracted by Notch filters. These components are mathematically modelled so that future predictions can be facilitated. In grid mode of operation, current is controlled based on the per component approach. In island mode of operation, a subsystem is singled out to be controlled by a per component voltage strategy.
In the second part of this study, model predictive controllers are designed for the various converters for both linear and non-linear loading. For this purpose, multi-synchronous reference frames are used to decompose converter and point of common coupling voltage and current quantities according to the needs of the control strategy. The cost function for each local controller extends to all components with an aim of regulating each component considered in the controls toward a set-out reference.

In the third part of this work, current components extractions under a non-ideal grid mode operation are investigated. Current components obtained from the multi-synchronous reference frames are compared with those obtained by the current physical components theory. Several loading conditions at the point of common coupling are considered under the effect of a grid voltage that is contaminated with negative sequence fundamental and positive/negative sequence harmonic voltage components.

Results obtained throughout this study prove the feasibility of the individual component approach in providing regulation. In addition, with the obtained components, power quality improvements, in terms of negative sequence voltage content, can be easily implemented.
ACKNOWLEDGMENTS

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Words cannot express my gratitude to my wife for her support and patience during the years of study. I am grateful to her for all the sacrifices she made for me. Thanks are also due to my sons, Ameen and Ali.

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Riyadh Toman Thahab Toman
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CHAPTER 1
INTRODUCTION

1.1 Introduction to Microgrids

Electric power generation, transmission and distribution is witnessing fundamental changes. These changes are characterized by a steady decline of classical centralized generation to local decentralized power sources. Localized energy sources, commonly referred to as Distributed Energy Resources (DERs), are found on large scale in distribution grids. Because of these sources, utilities have no longer passive but active distribution grids. The presence of these sources, however can undermine the reliability and safety of utility grids [1]. Besides some classical sources of energy, DERs are renewable energy sources that have power output as a function of randomly behaving environmental variables such as sun and wind. Electric wise, the randomness jeopardize the reliability of the supply which must maintain an equilibrium between the sums of generated and supplied power at any given instant. On the assumption of suitable coordinated control, these sources can provide many merits. These merits, such as power quality and reliability enhancement are not only technical, but also environmental such as complying with reduction of emission protocols [1].

To alleviate the challenges of DERs in distribution networks, the source may be connected in a grid fashion comprising what is known as a microgrid [1, 2]. Embedding DERs in a microgrid achieves better coordination and provide a platform to solve some of the problems associated with the vast invasion of these sources in utility grids [1]. It can
also better serve the needs of the utility grid. Perhaps a milestone of microgrids is the ability to disengage from the utility grid. This condition is referred to as islanding [3]. The utility grid and consumers are potential beneficiaries from the feature of islanding [2, 3]. Utility grids view the microgrid as a controllable unit that can separate in case of any sort of disturbance, with a continuous supply of power to consumers [4]. It is worth mentioning here that the scope of microgrid benefits are much broader than just its island capability especially when these grids are compared with single DERs from a functional point of view.

1.2 Microgrids Definition and Configuration

Although there is a good understanding of microgrid function (required coordination and components) no standard well know definition is documented yet [5]. In fact different views exist as to what is or what is not a microgrid. One approach is to view the microgrid as a system that encompasses different DERs and loads which breaks away from the grid to form an independent power supplying network [6]. An alternative approach to determine what is a microgrid and what is not is to compare functionality with another well-defined grid that also integrates DERs. This configuration is called the virtual power plant (VPP) [7]. Both microgrids and VPPs implement systematic integration of DERs [7] that have penetrated utility networks. However, quite a few differences exist and some can be summarized as [7]:

1. Microgrids can operate in autonomous and grid mode, however VPPs don’t endorse such a practice.

2. VPPs do not mandate storage elements such as batteries, flywheels, etc., whereas storage is an integral part of microgrids.
3. DERs in a microgrid lie within a well-defined area where the number of sources is known, whereas VPPs may include sources, different by nature and scattered in multi-areas across the distribution network.

4. Microgrids rely on devices such as intelligent power electronics converters but VPPs depend to a large extent on providing information and intelligent metering.

In addition to the above, VPPs main scope is to act as an integration platform for DERs. However, microgrids, one way or the other, invest in the needs of its customers [8].

In a broad sense, a microgrid can be defined as a unit composed of more than one energy source, various loads and energy storage devices that are harmonized to provide continuous electric power [5].

Microgrids can assume various configurations [2, 5]. One way to classify configuration is based on how many contact points the microgrid makes with its parent utility grid. This contact point is known as the point of common coupling (PCC) [5]. A general microgrid structure has one PCC with the utility [9], except in cases where a utility does not exist due to site or other limitations and the microgrid operates in continuous autonomous mode [5]. In general context, microgrids can also be shaped in the same way as distribution networks and basically can be radial, mesh or ring types [2]. Figure 1.1 shows a radial microgrid configuration with one PCC and four load feeders (F).
1.3 Stand-Alone Versus Microgrid Integration of Distributed Energy Sources

Microgrids require excessive amount of control and communication infrastructure to achieve the objective of a coordinated integration of DERs. As far as control is concerned, it is divided out into three layers or levels [10]. Each level should implement certain tasks to arrive at a well pronounced overall operation. In fact the objectives of some control levels are dependent on whether the microgrid is in autonomous mode or not. For example, if the utility grid is disconnected from the microgrid, controls have an objective of establishing and imposing voltage and frequency, a task taken care of by the utility grid in non-island mode [5]. Based on control complexity, one might argue that preserving DERs in stand-alone operation might be worthy than incorporating them in a grid fashion. However short and long term gains of such a systematic approach outweighs the complexity of the required control infrastructure. In Table 1.1, a list of benefits are
presented and a comparison is shown on how well a stand-alone DER versus a microgrid approach would compete per each benefit mentioned in [1,2,5, 11].

Table 1.1 Comparison Between Stand-alone DERs vs. Microgrids Integration

<table>
<thead>
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<th>Microgrid benefit</th>
<th>Stand-alone DER</th>
<th>Microgrid approach-Comments</th>
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<td>1</td>
<td>I²R losses reduction [2]</td>
<td>Yes, source in close vicinity to load</td>
<td>High reduction is achieved since a bulk of DER generation is close to the loads</td>
</tr>
<tr>
<td>2</td>
<td>Postpone expansion of transmission and distribution capacity to meet load elevation [1]</td>
<td>Can help in clipping peak loads, helping utilities to cure any power imbalances</td>
<td>Can supply a very large portion of peak load due to the aggregation of sources leaving utilities with flexibility leverage to cure power shortages over a wide spectrum of the grid</td>
</tr>
<tr>
<td>3</td>
<td>Vend extra generated energy to the main grid [5]</td>
<td>Yes, but depends on the capacity of the source</td>
<td>Large number of sources may result in surplus of power</td>
</tr>
<tr>
<td>4</td>
<td>A control layer that assess how to optimize generation to achieve goals [11]</td>
<td>No, since its only one source and not a variety of sources</td>
<td>Since the microgrid has a variety of sources- control loops can optimize generation according to setout factors</td>
</tr>
<tr>
<td>6</td>
<td>Provide sustainable power in case of prolonged absents of main grid [2]</td>
<td>No</td>
<td>Its viewed as a unit that can run its loads even when the main grid is disconnected [5]</td>
</tr>
<tr>
<td>7</td>
<td>Enhance power quality [2]</td>
<td>Unable to customize power quality</td>
<td>Able to customize power quality, at some or all buses</td>
</tr>
<tr>
<td>8</td>
<td>Take part in energy management program [2]</td>
<td>Yes</td>
<td>More evident</td>
</tr>
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</table>
The control levels of a microgrid are characterized by different time response and the groundwork requirements [5]. Here some control levels may need to act faster compared to others that can have a slower response. The first, second and third levels deal with reference generation for the internal control loops of DER, correct the frequency / amplitude of the microgrid voltage and controls bilateral power flows during grid mode of operation respectively [10]. The main aim of this dissertation concerns primary level control which directly deals with interfacing power converters.

1.4 Microgrid Sources and Interfacing Power Converters

A key feature of microgrids is that it can accommodate sources that vary by nature. For example some could be DC such as, photovoltaics (PV), fuel cells (FC) etc. While others supply AC power such as wind turbines (WT) and small hydro stations. Unlike VPPs, storage elements are considered a vital part of a successful functioning microgrid [7]. These elements work to preserve an equilibrium between consumed power with available capacity despite the variant output obtained from renewable energy sources [5]. To compensate for the expensive storage elements, an alternative is increase classical generation technologies [12] such as micro-turbines and synchrouns generators. In this way, the share of generation from non-intermittent sources is enhanced. Capacity of the microgrid non- intermittent sources have ranges in KW with micro turbines ranging from 5 to 100 kW whereas fuel cells range from 50 to 1 MW [8].
Interfacing of the various distributed sources to the microgrid depends on the nature of the source. Traditional source such as combined heat and power (CHP) generation and internal combustion engine require synchrouns or induction generator that are typically high inertia sources, other sources are interfaced electronically [13]. Power electronic converters play pivotal role in interfacing and/or power conditioning of DERs. Through these converters, power flow is controlled. The required interfacing mechanism for various DERs (that also include type of storages) and the control activities implemented are summarized in Table 1.2 below [13].

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<th>Power Flow Control</th>
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<td>Reciprocating engines</td>
<td>Synchronous generator</td>
<td>AVR and Governor control, (+P,±Q)</td>
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<td></td>
<td>Small hydro</td>
<td>Induction generator</td>
<td>Stall or pitch control of turbine (+P,-Q)</td>
</tr>
<tr>
<td></td>
<td>Fixed-speed wind turbine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonconventional DG</td>
<td>Variable-speed wind turbine</td>
<td>Power electronic converter (ac-dc-ac conversion)</td>
<td>Turbine speed and dc link voltage controls (+P,±Q)</td>
</tr>
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<td>Microturbine</td>
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<td>Solar PV</td>
<td>Power electronic converter (dc-dc-ac conversion)</td>
<td>MPPT and dc link Voltage controls (+P,±Q)</td>
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<td>Fuel cell</td>
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<td>Long-Term storage (DS)</td>
<td>Battery storage</td>
<td>Power electronic converter (dc-dc-ac conversion)</td>
<td>State –of-charge and/or output voltage/frequency control (±P,±Q)</td>
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<td>Fly wheel</td>
<td>Power electronic converter (ac-dc-ac conversion)</td>
<td>Speed control, (±P,±Q)</td>
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MPPT: maximum power point tracking, AVR: Automatic voltage regulation.
1.5 Dissertation Outline

- Chapter 1 presents an introduction to microgrids that include definitions and configuration.

- Chapter 2 presents literature surveying that include microgrid controls and in particular power converters control and implementation approaches.

- Chapter 3 derives mathematical model based on double synchronous reference frame of extracted voltage and current components and proposes a distributed finite control set-model predictive control based voltage and current control strategy for balanced and unbalanced loading.

- Chapter 4 extends microgrid converter control by the distributed finite control set-model predictive control to components that corresponds to linear and non-linear loading of the microgrid based on a multiple synchronous reference frames.

- Chapter 5 investigates converter control of microgrid connected to a non-ideal utility supply and compares extracted components by the synchronous reference frames to those obtained by the current physical component theory.

- Chapter 6 presents conclusions and future work.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Microgrids are required to implement several tasks because it represents a systematic configuration of various distributed sources and storage elements. These tasks are mode dependent. Beyond the provision of power to loads, which help to peel off peak loads, the microgrid can improvise a spectrum of ancillary services to the utility grid [14-17]. These ancillary can vary by nature, but a general frame include, frequency control, voltage control [14,15], and demand interruption [15]. The provision of these ancillary services could be a source of revenues [15] for microgrid owners. In fact, in literature the impact of ancillary services such as providing reserves is more effective when a bundle of microgrids are incorporated for this purpose [18].

2.2 Literature Review

The review carried out in this chapter concerns two aspects. The first aspect is related to the implementation of controllers for power converters. Since this level of the controls depends on the reference acquisition, the scope of the surveying will reach out to the approaches of reference determination.

The second aspect concerns the decomposition approaches that are found in literature. Power theory related decomposition and other approaches are explored.
2.2.1 Centralized Control of Power Converters

A fundamental principle of connecting several energy sources in parallel is to achieve adequate load sharing so that no circulating current flows which effects the performance of the sources. The way load current is shared among converters of parallel configuration depends on their output voltages [19]. Several factors play a role in providing imbalanced current sharing. These include inverters not being structurally identical nor impedances of connecting lines [19]. Control strategies, which by nature require crucial interlink between units, are commonly referred to as active load sharing strategies [19]. Type of approaches include current control [20], centralized controller [21], master-slave control [22, 23], average load sharing [24, 25] and current chain control (3C) [26, 27].

In the current control presented in [20] each parallel inverter has a PI controller from which the modulating signal is composed. In this work, no voltage control strategy is used and therefore the output bus voltage is determined from loading conditions of the entire system. Work presented in [21], uses a centralized voltage controller to calibrate the current error signal of the respective inverter unit. In this case each inverter supplies the same current, hence the reference setting for each controller, within a system of $N$ inverters, is equal to, $i_L/N$.

On the other hand, to eliminate a centralized controller, one of the units is selected to regulate the common bus voltage (called a master unit) and sets up the current reference that all other units must follow (slave units); such a system is referred to as a master-slave [22, 23]. As stated in [22] that such a control approach enables the connection of any number of inverters. The master unit can either be permanently allocated or units can take turns mastering, or a unit with the highest current rating is selected [19]. From a microgrid
prospective, a centralized or even a master-slave approach would require units to be in close vicinity and mastering unit should have an energy source that has no intermittent nature. An ideal candidate for such a master unit could either be fuel cells or battery packs as the primary source of energy. A master-slave scenario, where all slaves supply equal current as in [22] may prove impractical for controlling current feeding converters in a microgrid system due to the variety of sources and ultimately ratings.

Average load sharing method proposed in [24, 25] adopts an equal weight in load current sharing for each active unit. It is assumed that an information line that first accumulates current supplied by each unit, averages them according to the number of active units, and then sets the reference for the controller of each inverter. In [24] the authors proposed that any condition (s) that may deviate units from equal current sharing is modeled as a disturbance source. At the same time if the system is at steady state, the common bus voltage is a function of the individual voltage per unit. Authors in [26, 27] suggested a round chain approach for reference determination of a subsequent unit. In that sense in a $k$-unit system of energy sources, the current delivered by the $k - 1$ unit is set as a reference setting for the current controller of the $k$ unit. In both [26] and [27] each unit has an internal current and an external voltage control loop. However, in [27] a single voltage loop of a designated unit is active. Authors suggested that this reduces control interdependence and results in a more stable operation of the system. A link is essential to communicate supplied current to the $k$ unit controller.

The above methods for controlling inverters are used mainly in cases where the energy sources are very close to each other hence a link for signal transfer is possible. Controlling power converters for a microgrid needs some requirements such as plug and
play feature and the ability to expand the system without enduring much complications [28]. Work presented in [29] suggests splitting the controls into two parts based on the frequency of the controlled components. High frequency control variables are dealt with at the local level of the DER system. Low frequency components are managed centrally, from which reference setting are transmitted to local controllers using less demanding link.

2.2.2 Decentralized Control of Power Converters

The trait of the decentralized approach is the elimination of crucial communication links between units. It is implemented in controlling synchrouns generators [30] connected in parallel to a common bus. This approach has been applied to control energy sources interfaced through power converters [31,32,34,35,36] that could be dispersed over a wide area and in low voltage electric grids [33]. Fundamentally, decentralized control is implemented based on measurements of voltage and frequency at the terminals of the unit [34]. For an inductive line with a small phase difference between generated and common bus voltage, the active and reactive power is proportional to both phase difference (eventually frequency) and generated voltage [30] respectively. These are referred as, $P - f$ and $Q - V$ droops [32].

This kind of control is implemented when more than one converter is in operation for supplying load. Load division will depend on the slope parameter of droop lines for individual units [30]. An approach of a communication less control of distributed energy sources interfaced through power converters using frequency droop is presented in [37]. The authors suggested constructing the amplitude and phase of the converter modulating signals from one of two possible loops. A P-f droop or a maximum power loop can be employed to determine the phase. The amplitude of the modulating signal is obtained from
either terminal voltage control or maximum current loop. In all loops, only domestic measurements of voltage, current and power are needed.

Despite its potentials, droop control suffers from several drawbacks. These include [5, 30];

1. The performance of the droop method is very sensitive to the $R/X$ ratio of lines connecting units to PCC.
2. Droop method is unable to share current harmonics of connected non-linear loads.
3. The method gives no consideration to the dynamics governing the load behavior, which could produce malfunction of the controller in an abrupt change of load.
4. Non-satisfactory sharing during transient periods because the active and reactive powers used in $P - f$ and $Q - V$ droops are mean values.

All the listed disadvantages presented problems for a microgrid. For example, low voltage microgrids at distribution grids have lines with high $R/X$ ratio that effects both droops due the P and Q coupling [38]. This will degrade the load sharing. Also, harmonic current results from a vast spectrum of non-linear loads needed to be shared by the microgrid units.

Several researchers suggested ways of improving the droop control [39-42]. In [39] authors proposed additional transient term to the droop relations. Gain of this term is determined by the pole placement method. Results demonstrated considerable improvements in the poor transient response of conventional droop in terms of the startup current of a microgrid unit and dynamic power response. Virtual output impedance has been suggested to improve the performance of the usual droop control [40, 41]. In [40] an inductive impedance is designed to decouple powers and achieve accurate load sharing.
Authors report that the presented approach shows very good performance with respect to alleviation of the effect of voltage components that are in orders of the fundamental frequency under non-linear loading conditions. Authors in [41] presented a modified droop control for parallel inverters in a low voltage microgrid. In this work, a resistive virtual impedance is designed such that the system has an immunity to oscillations. Authors report that such impedance at inverter terminals provides implicitly a share of harmonic load current components. Decoupling powers can also be achieved by axes transform as in [42]. This transform involves an angle defined by the impedance of the connecting line of the microgrid unit.

Although some of the drawbacks have been dealt with, perhaps remedying every drawback mentioned in droop based control result in a more demanding and perhaps a costly controller.

2.2.3 Control Tiers of Microgrids

To fully exploit the microgrid services, especially in impacting demand response in order to enhance reliability indices and executing energy management programs efficiently, a full control architecture should exist. For example, if the utility grid suffers a power/demand mismatch that decelerates the utility, microgrid units can offer a demand response to restore the power balance. This requires external coordination between grid management system and the microgrid main controller. Internal action, within the microgrid units, is to change reference settings and eventually increase the injected power to the upstream grid. Therefore microgrid control architecture are divided into three tiers; primary, secondary and tertiary [43-46]. These tiers operate at different bandwidths so that no overlap of dynamic occurs [43]. Part of the primary level is the actual implementation
of the voltage and/or current loops of the converter interfacing the energy source which is referred to as zero level [44]. Figure 2.1 shows a diagram of the duties each level has to undertake. Authors in [43-45] presented a one centralized structure for the secondary level, where voltage and frequency are measured at the PCC of the microgrid. Two control loops, one for magnitude and the other for frequency, produce an error. This error is processed in a proportional plus integral controller to generate control signals that are communicated to the primary level relevant to each DER unit. Certainly this would still require a communication network that interact with every DER unit that is in service in the microgrid.

Work in [45] proposed a secondary level that also improves power quality at the load bus. Authors proposed, in addition to the two loops (voltage magnitude and frequency), a third loop which controls the voltage unbalanced factor that reflects the amount of negative sequence component in the bus voltage. All three reference settings are communicated to local primaries of units. More recently, distributed approaches are suggested to implement secondary level controls [47-49]. These distributed approaches free the system from communication networks, which makes the controls less susceptible to failures. A distributed approach of secondary control level is presented in [47]. In this approach, a cooperative scheme is proposed in which each DER unit communicate with adjacent unit in order to correct voltage and frequency in addition to its own local measurements. In this way a less demanding communication is required.
In [48], a distributed approach is presented in which voltage magnitude and frequency deviation at the load bus of a microgrid are nullified in a finite-time. Two advantages are reported compared to other distributed approaches. The first is that the voltage magnitude and frequency loops can be designed independently. The second advantage is that implementation of secondary control is integrated in the primary control.
of the DER unit. In that respect, the primary controls is complemented with an input vector that corresponds to secondary control variables.

Authors in [50] presented frequency control of an islanded microgrid based on classifying each unit as an agent. The main objective is to eliminate frequency deviation due to any power mismatch by cooperative action between agents. Here, agents obtain details about the power inconsistency and each unit work with others, to eliminate the deviation through actions that can include turning off loads. Results reported by authors confirm the effectiveness of the method even in contingency situations.

2.2.4 Implementation of Voltage and Current Controllers of Interfacing Converters

Interfacing converters have a key role in accomplishing all orders from local or upstream level controllers. The purpose is eventually to set control variables to their targets or reference settings. Power converters through which DER sources supply energy can be classified based on the role which they play. Converters for microgrid units that setup nominal voltage during island mode are grid forming whereas converters of units that supply current are grid following [52]. The former exists only if the microgrid is deliberately or not deliberately islanded however the latter can exist regardless of the mode of operation [52]. However, a third category which has a main duty of forming or feeding with additional regulation are referred to as voltage or current supporting converters [53]. For example, current supporting converters, with the main objective of injecting a regulated amount of active/reactive power, are extra tasked to maintain voltage magnitude and frequency of the PCC [53].

The main type of converter that is used between the energy source and the terminals of the microgrid is the DC/AC. However, other sources may require an intermediate
converter between the terminals of the source and the DC source. For example, a photovoltaic (PV) source require a DC/DC stage for tracking the peak power of its generating characteristics which continuously alters due to dependency on the falling light across the array. Another example is a wind turbine generator with a double fed induction generator. A DC/DC stage is needed to provide a dc link to the accumulated power that is then converted to AC via the DC/AC converter.

Grid forming converters (with no support action) which are voltage controlled have a voltage reference setting determined from $p - f$ (phase) and $Q - V$ droops (magnitude) if a non-communication approach is adopted [52]. This reference is projected into three phase modulating signals and the conventional pulse width modulation controls the switching action. The main approach of implementing converter control of a grid forming converter is to use the conventional proportional plus integral controller (PI) [53, 54]. A control loop with or without an internal embedded current loop [54] is designed to achieve voltage regulation of both magnitude and frequency. Authors in [55] proposed a voltage based control of a local DER in a mesh topology microgrid. The approach defines a management center that implement a rapid load flow analyses between different buses of the microgrid, from which voltage magnitude and phase shift are determined for each bus. Tracking of voltage bus is achieved by a linear time invariant (LTI) - multivariable servomechanism controller. Robustness and stability issues are also investigated in that work.

Authors in [56] presented an $H_{\infty}$ controller for grid forming converter. The design procedure for this work consisted of formulating the problem at hand and selection of weighted functions. This is realized by using linear matrix inequalities and modification
process to arrive at a simple but reliable controller. The authors’ showed the performance of this converter by paralleling it with a grid feeding converter to supply balanced LTI loads only.

Grid feeding converters are operated to inject controlled current [52] or respond to demand increase. These converters can be of two level or more topologies. Hence they are controlled as current sources that have very high parallel impedance [53]. Controllers for this type of converters are designed either in stationary abc or αβ reference frame. A rotating reference frame that rotates in synchronism with the grid can be used which results in control variables appearing as DC components. This enables the implementation of the control by conventional PI controller [5]. In [57], an approach is presented to design a current controller in dq synchronous reference frame to regulate currents then a dq/abc transformation enables implementation in abc frame. Authors report that the stationary frame controller exhibits terms that reflect the interaction between current phases. Conventional PI controllers show a weak response to offsetting steady state errors when both reference and actual current signals are of AC nature [58,59]. An alternative that offer potential regulation capabilities is the Proportional+ Resonant controller ($P + PR$) [58, 59, 60]. These controllers have:

1. A very high gain at the controller resonant frequency, that enable it to respond rapidly with a zero [61] or near zero steady state error.

2. A harmonic compensator that extract harmonic components corresponding to the designed resonant frequency and sets a reference that can be incorporated in the controller [61].
Even with the aforementioned harmonic compensator, the performance of the $P + PR$ is not affected since the controller and compensator act on different resonant frequencies [61]. Application of $P + PR$ in controlling interfacing power converters, as part of an islanded microgrid or utility grid maybe undermined. This is due to the expected frequency drift [61]. A Bode analyses presented in [62] shows that a $P + PR$ controller achieves nearly infinite gain in a discrete venue at the resonant frequency, whereas for the vicinity around the resonant frequency the gain is significantly reduced. Frequency deviation in electric networks is a function of the balance between generation and demand. This balanced is constantly a concern especially in microgrids that have their utility grid disconnected.

Deadbeat control is another potential choice for regulating sinusoidal controlled variables and it is regarded as a type of prediction control approach [61]. According to the deadbeat control, a control variable of a linear system can be regulated to a steady state value in a minimum time steps. In this aspect, the poles of the closed loop transfer function are brought to the $Z = 0$ location on the Z-plane. Hence, any steady state error (s) of control variable (s) are attained to zero. This type of control has been implemented for power converters in [63, 64]. However, with respect to a deadbeat control of converters three concerns are brought up:

1. The control variable can attain steady state with zero error in a period of samples equal to the order of the system if the magnitude of the control action is not restricted [65]. However, voltage signals corresponding to the finite switching pattern constrains the control action as far as power converters are concerned.
2. The presence of an LCL filter in the actual converter circuit derives some poles to the verge of the instability region and hence it risks instability at the onset of a slight disturbance [61].

3. Sensitive to parameter drifting which could undermine the robustness of the controller [61].

Authors in [61] proposed a method of varying the gain factor thereby increasing the damping which supplement immunity to parameter drifting, on one hand, and pulls back the poles with higher frequency within the vicinity of the $Z = 1$, on the other. It is worth mentioning that power converters controlled to track a desired reference, for example current, need to satisfy not only minimum error but also a rapid response [66] to a sudden change in desired setting. In a microgrid system, a change of setting can result from an increase or decrease in the share of one of the units connected at the PCC.

Model predictive control (MPC) is a control approach that have seen a spectrum of industrial applications such as, chemical plants, production plants and air traffic control. Future control actions in MPC are obtained by solving an optimization problem that uses the current state of the system. A vector of control actions, the length of which is defined as the control horizon [67], is obtained from a prediction vector of the state (s) of the system. The length of the prediction horizon window is a design consideration. To use the more updated information about the state (s) behavior, only the first control action is executed by the controller and such a control is referred to as receding horizon [67]. A model of the plant is the vital aspect of MPC.

Power converters are attractive area for application of MPC. A discrete form of MPC, employed in the control of converters, is the finite control set-model predictive
control (FCS-MPC) [68,69]. A concern that limited the application of MPC, is the computational effort involved in a very short time [70]. However, in the era of fast speed processors that are available today, this is no longer considered a primary limitation [70]. Authors in [71] presented an FCS-MPC method to control the load current of an RL load with a back emf source. A model that predicts future load current and a cost function, that minimizes the difference from an extrapolated reference and actual currents, are used. The controller is implemented in the stationary $\alpha\beta$ frame.

Current control in [72] is suggested to a load fed through a four-leg inverter. In that study, where stationary frame is used, the cost function penalizes the deviation of each phase current from a defined reference setting. Application of MPC that involves control of electric drives is presented in [73]. In this work, a current controller is implemented for a multi-phase electric drive. Results are verified on an AC motor drive. The authors discuss several important aspects of FCS-MPC such as the nature of the cost function, control of switching frequencies and required time to get the optimum switching pattern.

Power converters that are controlled as voltage source inverters with FCS-MPC are presented in $\alpha\beta$ stationary frame in [74-76]. In these studies, a converter is assumed to supply an isolated load and the inverter is operated to produce controlled voltage. A current observer is suggested in [74] to approximate the load side current. Beyond the two level, MPC has also been applied to converters for high power applications [77-79]. In [78], power control has been implemented with the objective of pumping controlled power into an existing grid. The cost function implemented accounted for power tracking errors, capacitor voltage balancing and switching action minimization. In [79], current strategy is used to control the four level diode clamped inverter tied to an existing power grid. In this
work, in addition to the current tracking and switching minimization terms, the third term of the cost function accounted for regulating the dc link capacitor because the energy source in the study is a non-dispatchable wind turbine. The last two terms are weighted so that when minimizing the cost function priority is given to the tracking terms.

One of the potentials of FCS-MPC is the flexibility of incorporating additional terms in the cost function [68, 69]. However, this may result in degrading the main control objective. For this reason additional terms in the cost function are scaled by weights [69, 80] so as to give the upper hand to the main control objectives. It is suffice to say here that the values of the weights used in additional terms of the cost functions are selected by assuming values and examining the control performance [68]. Although weight selection directions are presented [80], and in [81] authors presented an approach that relates the determination of weight as part of the optimization process.

To extend MPC applications to composite, large, and span wise diverse systems such as a microgrid system requires different tackling approach. Centralized MPC involves minimization of one cost function, using one composite model for the whole system, shows accurate control performance, but maybe tedious [82] and costly to implement. Hence it is viable to partition the overall large system into smaller systems to be controlled in a non-centralized fashion [82]. Non-centralized approaches of MPC basically divides a large system into subsystems, where each subsystem has its associated controller and action calculating unit [83]. Implementation wise, non-centralized MPC can be classified as decentralized and distributed schemes [84]. The distinct feature between a decentralized and a distributed approach lies in the way of how information is conveyed (if any) between local controllers to achieve global system objectives.
Decentralized approaches of MPC have no exchange of information between controllers of subsystems [85]. A local controller of an $i^{th}$ subsystem ($i = 1, 2, 3, ... m$) calculates control actions to be applied at instant $+1$, $Ui(k + 1)$ based on predictions of local states based on satisfying a local control objective. Authors in [86] suggested a decentralized MPC to control a process. In this study the overall model of the system is portioned into models for local subsystems. Here, a local controller solves an optimization problem to get the optimal control action. This information may be shared with other controllers based on how strong or weak is the interaction between subsystems. The authors suggested that if stability conditions are not satisfied, local models are modified to include interaction between subsystems. This increases communications between controllers of local systems. The authors included in their study the impact of a sudden miscommunication between controllers. The implementation of the proposed approach is carried out on temperature regulation in a multi-zone area.

Authors in [87], presented a method of replacing a centralized MPC by a number of local MPCs. Each local controller determines a set of control actions based on measurements at instant $K$ of state variables of the system, with information from adjacent subsystems. In this work, the authors represented a system as a node with a path that describes the coupling between subsystems. The authors adopts a receding horizon approach for implementation of control actions where only the first action, from a vector of optimal actions, is executed.

Decentralized MPC approaches have been implemented on conventional power systems since these systems are potentially large and interconnected. The main objective of local controls, which represents an area, is to off-set frequency deviation and eventually
achieve power generation/demand equilibrium [88, 89]. Authors in [88] presented an MPC approach that controls a multi-area power system with tie lines. The way control is implemented relies on local measurements of a subsystem and a one-time access to relevant information of nearby zones. This results in a near decentralized implementation structure with small communication needs. Reported merits of this method is a less complicated control system in addition to an inherited closed loop stability.

Authors in [89] provide an evaluation of three non-decentralized MPC approaches to achieve power balancing in power networks. The study evaluated a completely decentralized MPC, stability constrained distributed MPC and feasible cooperation based MPC. Based on the results provided, the authors reported that:

1. MPC approaches that require small scale communications between nearby subsystems can be more practical as far as controlling electric power systems. That is, limited communication links between MPCs are more practically feasible compared to a centralized or a highly communication demanding approach.

2. An MPC approach without any inter-communication between other local areas provide a superior performance compared to the commonly used open loop power scheduling (automatic generation control).

3. Distributed MPC approaches can provide enhanced performance but these merits should not be a call for wide communication links that could hinder implementation of the control system on the ground.

Distributed Model Predictive Control (DMPC) approach accommodates flow of data between local controllers of subsystems [85]. This data can includes predicted states and/or the computed control actions. DMPC is viewed as a compromise control approach
between two different schemes that are fully centralized and decentralized MPCs [90]. DMPC is based on a cooperative or non-cooperative [90]. In non-cooperative DMPC, predictions of state variables carried out by the $i^{th}$ local system on behalf of other subsystems, do not concur with those made by the subsystem itself [91]. The authors in [91] proposed a strategy for a large control system based on a non-cooperative approach. The subsystems comprising from the large system are assumed to be couple via dynamics or the variables constraints. Priorities are assigned to each subsystem. Hence a subsystem that has the minimum assigned priority needs to make concur predictions with all subsystems if a coupling path exists. Evaluation of the method is compared with a centralized MPC. Communication based DMPC is suggested in [92] based on a multi-subsystems negotiation. Several proposed solutions are set out and only one is adopted according a specified criteria.

From industrial systems to renewable sources and power systems, DMPC has been applied in large systems [93, 94] that cannot be controlled by a centralized approach. In [93], a multi-turbine wind farm is controlled by a DMPC approach to achieve a system wide objective. Each wind turbine structure has a local MPC controller. The control law obtained is optimal, distributed and cooperative because it considers fatigue reduction, relies on domestic measurements of a turbine and information is exchanged with neighboring subsystems only. Authors in [94], presented a power system based application of a cooperative possibly iterative DMPC. In this work generation control in a large power networks in which two and four area zones are considered. The global objective is maintaining a constant frequency under load power changes. Each subsystem has a relevant MPC controller that determines control actions from a set of data that provides model based
predictions of subsystem behavior. The authors proposed that computations of a subsystem can be iterative, where information is exchanged more than once if ample time is available.

MPC approaches for control of converters have been applied to either a converter hooked up to an existing grid or stand-alone system which inherently involves one converter. Applications such as microgrid systems that involves a number of DER source (and eventually interfacing converter) have seen little work [95]. In microgrid system, there is a need for a distributed MPC, especially in mesh topology microgrids where tie lines exist between various subsystems enhancing interactions in states, inputs or both. An approach that decomposes the control into transient and steady state problem is presented in [95]. The transient part is solved by a conventional MPC approach, which penalizes the difference between predicted and reference setting. The transient part of the control signal is calculated based on dynamic MPC method. Hence the required sampling time can be greatly reduced. The proposed method is implemented on a four unit microgrid that are in mesh topology and modelling includes the interacting states between the units. Grid and island modes are both investigated. Authors in [96] proposed a centralized MPC for an \( n \) connected inverters that are connected in parallel for an uninterruptable power supply (UPS). A composite model for the system is developed which includes inserted integrator to offset errors. A three term composite cost function is used for the entire system. The terms penalize voltage regulation error, minimizing circulating current between units and constrains of the control actions.

2.2.5 Decomposition and Related Power Theories

Decomposition of current into components have been primarily correlated to the power theories. These power theories, which explain load related phenomena, eventually
lead to current components. Theories such as the instantaneous power theory, Fryze-Buchholz-Derponbrock (FBD), conservative power theory (CPT) and the current physical component theory (CPCT) provide current components [97-99] with different approaches on the way they are determined. The instantaneous p-q theory, based on the stationary frame abc/αβ transform, decomposes power into instantaneous active, reactive and zero sequence [97]. The abc stationary frame active and reactive currents are obtained from these powers. The conservative power theory (CPT) defines total active and reactive energies. The total current is decomposed into active, reactive, and residual (void) currents [98]. Residual current is the difference between total current, active and reactive components.

The current physical component theory (CPCT) breaks current into orthogonal components [99]. In case of a linear time invariant (LTI) load with harmonics and/or asymmetries free voltage supply, the current is decomposed into active, reactive and unbalanced components at the fundamental frequency [99].

Work related to microgrids based on CPT theory is presented in [100, 54]. In [100] CPT is used to determine contribution of source and load in subsidizing unbalance and harmonic components that results in an unbalanced and distorted PCC voltage profile. The procedure outlined is based on approximating active, reactive and void power quantities under the assumption of balanced voltage supply. The difference between actual and approximated terms are asymmetry and distortion components are source affiliated. Authors term this process as “accountability” in smart microgrids. The study extends to control of compensator units. Authors in [54] used the CPT to decompose PCC current.
Authors generated reference current signal by linearly scaling the current components. A PI controller is used to provide the tracking of converter current.

Utilization of CPCT in providing components for decentralized coordinated control of converters for two DER sources in island mode is presented in [101]. In this work, current decomposition is implemented by CPCT and resulting components are shared by current based droop approach. It is reported that in case of the DER being a renewable source, the active current component can be obtained from a loop that detects peak power operating point. In [102] control of shunt compensator is presented. In that approach CPCT is used to setup reference current for each compensator based on factors for each component. Here one reference is obtained by adding up all product of scale factors by current components. Current tracking is achieved by a predictive control that is implemented in receding horizon fashion. Work presented in [103] suggested control of a grid converter under non-sinusoidal voltage conditions. The authors used the CPCT potentials in providing current components under asymmetrical and distorted supply. Resonant controller is used to provide control of current towards the reference setting.

Fryze pointed out that the consumption of real power by a load is determined by the real value of an equivalent conductance $G_e$ [104] as seen by the voltage source. A current component calculated based on $G_e$ is called the active component [104]. According to the FBD theory, current is decomposed into active, non-active, power, powerless, and variation components [105].

Synchronous reference frame is a decomposition approach that defines components based on symmetrical components [106]. In a condition where only positive and negative sequence component exist, two rotating frames are needed and the decomposition is
referred to as double synchronous reference frames (DSRF) [107]. DSRF have been used to
decompose grid current during transient voltage dips that lead to unbalanced conditions
[108, 109]. Authors in [108] reported that extraction of a sequence component, from the
double frequency ripple of the other sequence, is carried out by the signal delay
cancellation. However, authors in [109] presented an approach of obtaining a sequence
cOMPONENT by injection of a term which is equal to the double frequency ripple of the other
sequence in opposite sign so that the required sequence can be obtained.

The multiple synchronous reference frames (MSRF) have been suggested to estimate
harmonic content in signals where a number of synchronous reference frames are needed
[110]. Authors in [111] presented an approach of obtaining the fundamental positive
sequence voltage through MSRF decomposition of a voltage that is polluted by positive/
negative sequence fundamental and harmonic voltage components. Then phase locked loop
is then used to detect the grid angle, which can be used in various control processes. Other
applications of MSRF concern detection of harmonic current for compensation, as in active
filters [112, 113], where only a nonlinear load or a defined distorted signal is analyzed
using this approach.

2.3 Goals of This Dissertation

A microgrid can offer several services for both modes of operation. At the grid
mode, different services such as demand response, alleviate loads at peak day times, which
is a priority. In chapter 1.0, different ancillary services that can be incorporated to expand
the scope of operation of the microgrid were outlined. The nature of the load current of a
microgrid resembles that of a conventional utility grid. To carry out the above task a
powerful and more targeted control is needed at lower tiers of the hierarchy. Providing
such a control can be achieved if the voltage and current quantities can be decomposed into components that reflect the nature of PCC loads. Other tasks such as compensation or power quality control can be streamlined by targeting a specific current or voltage component related to the process. For example, if power quality defined in terms of how much negative sequence voltage is present at a bus (or even PCC) relative to nominal positive sequence voltage, it can be evaluated, manipulated and controlled through the extracted negative sequence component.

Based on what have been presented in the literature review, there are two objectives in this work. The first objective is to investigate the decomposition of load current into components using double and multiple synchrons reference frames (D/MSRFs). This includes a new field of application for D/MSRFs where assessment of its feasibility is investigated. Voltage quantities relevant to the control approach are also decomposed by D/MSRFs. Decomposition is followed by extraction of the required components. Similar decomposition action is implemented on converter quantities of grid forming or grid following units associated with the adopted control approach.

The second objective is to propose a control approach where each extracted component is regulated to a reference setting. Controller for each unit in the microgrid, which is viewed as a subsystem, is designed and implemented using a distributed FCS-MPC. Here each unit has a local objective which can contribute the global objective of the entire microgrid system. Each subsystems’ controller relies on local measurements, which are acquired as individual components, and common states which are the PCC voltage, for the considered topology. Hence, PCC voltage is also decomposed and a component by component extraction is employed and used in the relevant model of a subsystem controlled
variable. Global objective is mode dependent. For example in grid mode, converters regulate current components towards their reference settings and load/demand balancing is achieved. In island mode, the global objective is achieving nominal voltage and frequency at the PCC which is controlled by one unit. The other converters must regulate load current in a per component fashion to maintain a stable frequency. The considered topology in this work is radial and hence controllers of local system need not to communicate.

Coordination between grid following units are achieved by share factors that are communicated from a microgrid controller. In this work, it is assumed that a unit with a dispatchable source is controlled as a voltage source inverter. This converter,

1. sets up and controls the voltage of the microgrid during an island event,
2. supplies the difference between load current and total current supplied by all switched grid following (in per component), and
3. nullifies all voltage fundamental negative sequence and harmonic components through its FCS-MPC local controller.

Grid following converters are controlled to supply current in a per component approach. In this work power quality issues such as minimization of negative sequence voltage is achieved at the primary level through the composite function of the FCS-MPC without the need of other control level intervention.
3.1 Introduction

Power converters in a microgrid are classified by the way they are operated to achieve the control objectives. In microgrids with a variety of energy sources, these converters either convert power into AC form or condition it when the source itself is not of a DC nature. A unit in a microgrid, which basically includes the distributed energy resource (DER) and associated power converter, have either one of the following two tasks depending on the mode of operation of a microgrid [5]:

a. Respond to load demand with the available power from the DER.

b. Establish and tightly control voltage and frequency.

Therefore, converters that are controlled to supply current are called grid following (GFE), whereas ones that are voltage controlled are grid forming (GF) [52]. In this chapter two types of load that are connected at the PCC, balanced and unbalanced are considered. Furthermore, it is assumed that all loads are clustered at one point in the PCC. Figure 3.1, shows the microgrid system under consideration. In this system we have an $n$ by $k$ subsystems that are operated as GFs and GFEs respectively.
3.2 Synchronous Reference Frame Decomposition

Based on the SRF, a quantity can be expressed in terms of positive and negative symmetrical components [109]. Since we have balanced and unbalanced loads, microgrid quantities will have two components, a fundamental positive and negative sequence components. Given an $X$ microgrid quantity (voltage or current in stationary $\alpha\beta$ frame), the SRF for balanced and unbalanced decomposition in terms of symmetrical components, can be written as,
\[ X_{a\beta} = X_{dq}^+ e^{j\omega t} + X_{dq}^- e^{-j\omega t} + X^0 \]  

(3.1)

If the system has no fourth wire, the zero sequence component \( X^0 \) can be ignored [114]. To extract the fundamental positive sequence, (3.1) is multiplied by \( e^{-j\omega t} \),

\[ X_{a\beta} e^{-j\omega t} = X_{dq}^+ + X_{dq}^- e^{-j2\omega t} \]  

(3.2)

To extract the negative sequence, (3.1) is multiplied by \( e^{j\omega t} \) and this gives,

\[ X_{a\beta} e^{j\omega t} = X_{dq}^+ e^{j2\omega t} + X_{dq}^- \]  

(3.3)

The components, which are further processed in the FCS-MPC of a subsystem, are embedded in AC ripples that rotate at double the fundamental frequency as shown by (3.2) and (3.3). Extraction of the targeted component can be achieved by filtering techniques or by delay signal cancellation (DSC) [114]. In this work, a notch filter [115] is suitably designed to extract the sequence components.

### 3.2.1 Example of Decomposition under Unbalanced Loading Conditions

In this section an example is considered to get a numerical feel of the SRF decomposition. A balanced load with total power of \( S = 9 + j6 \, KVA \) is connected across the PCC with a two phase of \( S_{2\phi} = 4 + j2.8 \, KVA \) between phase (a and b). For a high short circuit level grid with 208 V (L-L), the instantaneous current in dq-axis is found to be:

\[ i_{d(t)}^{+1} = 47.41 - 15.95 \cos(2\omega t + \phi_1) \]

\[ i_{q(t)}^{+1} = -34.85 + 4.803 \sin(2\omega t + \phi_1) \]
\[ i_{d(t)}^{-1} = -15.95 + 47.41 \cos(2\omega t + \phi_o) \]

\[ i_{q(t)}^{-1} = 4.803 - 34.8 \sin(2\omega t + \phi_o) \]

PCC voltage components for positive and negative sequence which corresponds to the high short circuit KVA are,

\[ V_{d}^{+1} = 169.6 \, V, V_{q}^{+1} = -0.1083 \, V, V_{d}^{-1} = 0.01413 \, V \text{ and } V_{q}^{-1} = -0.06984 \, V \]

Here all negative sequence voltage components are very low this is due to the corresponding negative sequence voltage drop. If a weak grid is considered with a high Thevenin’s impedance, the current sequence decompositions for this case are,

\[ i_{d(t)}^{+1} = 35.26 - 7.346 \cos(2\omega t + \phi_1) \]

\[ i_{q(t)}^{+1} = -20.51 + 3.904 \sin(2\omega t + \phi_1) \]

\[ i_{d(t)}^{-1} = -7.346 + 35.26 \cos(2\omega t + \phi_o) \]

\[ i_{q(t)}^{-1} = 3.904 - 20.51 \sin(2\omega t + \phi_o) \]

As for the PCC voltage decomposition, components are expressed as follows (voltage phase angle not expressed for simplicity):

\[ v_{d(t)}^{+1} = 119.7 + 7.367 \cos(2\omega t) \]

\[ v_{q(t)}^{+1} = 11.39 - 7.467 \sin(2\omega t) \]
\[ v_{d(t)}^{-1} = 7.367 + 119.7 \cos(2\omega t) \]
\[ v_{q(t)}^{-1} = -7.467 + 11.39 \sin(2\omega t) \]

The negative sequence voltage drop is evident, where terms that express opposite sequence rotate at double the frequency.

### 3.3 Component Based Control for a Grid Forming Subsystem

In island mode GF converters set up nominal voltage and frequency which are normally dictated by the utility grid during grid mode [5]. The aim of this section is to design an MPC that regulates the PCC voltage towards its nominal value. The controller of this subsystem relies on local measurements which are filter current, filter capacitor voltage and the output current of the converter. Here the PCC voltage is indirectly controlled via the capacitor voltage.

#### 3.3.1 Extraction and Modelling of Grid Forming Control Quantities

Based on eqs. (3.2) and (3.3), the voltage across the capacitor, filter current and output current of the \( n^{th} \) GF converter subsystem can be expressed in SRF as,

\[
V_{a\beta f} e^{-j\omega t} = V_{dqf}^{-1} + V_{dqf}^{-1} e^{-j2\omega t} \\
V_{a\beta f} e^{j\omega t} = V_{dqf}^{-1} e^{j2\omega t} + V_{dqf}^{-1} \\
V_{a\beta f} e^{-j\omega t} = i_{dqf} + i_{dqf} e^{-j2\omega t} \\
i_{a\beta f} e^{j\omega t} = i_{dqf} e^{j2\omega t} + i_{dqf}^{-1} \\
i_{a\beta f} e^{-j\omega t} = i_{dqf} + i_{dqf} e^{-j2\omega t} \\
i_{a\beta f} e^{j\omega t} = i_{dqg} + i_{dqg} e^{j2\omega t} + i_{dqg}^{-1} \\
i_{a\beta g} e^{-j\omega t} = i_{dqg} + i_{dqg} e^{-j2\omega t} \\
i_{a\beta g} e^{j\omega t} = i_{dqg} e^{j2\omega t} + i_{dqg}^{-1} \\
\]
where $V_{dqf}, i_{dqf}$ and $i_{dqg}$ are the capacitor voltage, filter and output converter currents for the $n^{th}$ GF subsystem converter per sequence component in SRF respectively. The current balance at the capacitor junction is expressed in space vector [116] as,

$$C_g \frac{d\bar{V}_f}{dt} = \bar{i}_f - \bar{i}_g$$  (3.7)

To convert to SRF, voltage space vector, for example, is expressed in terms of dq axes by [116],

$$\bar{V}_f = V_{dqf}^+ e^{j(\omega t + \delta_o)}$$  (3.8)

where $\delta_o$ is the initial phase shift. Equation (3.8) is defined for positive sequence rotation, to account for the negative sequence component (3.8) becomes (initial phase shift neglected),

$$\bar{V}_f = V_{dqf}^- e^{-j\omega t}$$  (3.9)

By separately substituting (3.8) and (3.9) into (3.7) for each sequence, the current balance per positive and negative sequence components are expressed as,

$$C_g \frac{d(V_{dqf}^+ e^{j\omega t})}{dt} = i_{dqf}^+ e^{j\omega t} - i_{dqg}^+ e^{j\omega t}$$  (3.10)

And the negative sequence is,

$$C_g \frac{d(V_{dqf}^- e^{-j\omega t})}{dt} = i_{dqf}^- e^{-j\omega t} - i_{dqg}^- e^{-j\omega t}$$  (3.11)
where \( C_g \) is the filter capacitance. Solving for the derivative and with some simplifications, an expression for the rate of change of positive and negative voltage component, per axis, across a GF subsystem capacitor is as in (3.12) and (3.13) respectively

\[
C_g \frac{dV_{af}^+}{dt} = C_g \omega V_{af}^+ + i_{af}^+ - i_{ag}^+
\]

(3.12)

\[
C_g \frac{dV_{af}^-}{dt} = -C_g \omega V_{af}^- + i_{af}^- - i_{ag}^-
\]

(3.13)

The final part of the governing equations is related to the voltage balance for the filter of the GF converter. Following a similar procedure positive and negative sequence components are expressed as,

\[
L_g \frac{d(i_{af}^+ e^{j \omega t})}{dt} = -j \omega L_g i_{af}^+ e^{j \omega t} - R_g i_{af}^+ e^{j \omega t} - V_{af}^+ e^{j \omega t} + V_{af0}^+ e^{j \omega t}
\]

(3.14)

\[
L_g \frac{d(i_{af}^- e^{-j \omega t})}{dt} = j \omega L_g i_{af}^- e^{-j \omega t} - R_g i_{af}^- e^{-j \omega t} - V_{af}^- e^{-j \omega t} + V_{af0}^- e^{-j \omega t}
\]

(3.15)

where \( R_g, L_g \) and \( V_{af0} \) are filter resistance, inductance and output voltage of GF subsystem converter. The voltage, \( V_{af0} \) is function of the switching pattern. On a per axis and for positive and negative sequence, the rate of change of current is expressed as,

\[
L_g \frac{di_{af}^+}{dt} = L_g \omega i_{af}^+ - R_g i_{af}^+ - V_{af}^+ + V_{af0}^+
\]

(3.16)

\[
L_g \frac{di_{af}^-}{dt} = -L_g \omega i_{af}^- - R_g i_{af}^- - V_{af}^- + V_{af0}^-
\]
\[
L_g \frac{d i_{af}^{-1}}{d t} = -L_g \omega i_{qf}^{-1} - R_g i_{af}^{-1} - V_{af}^{-1} + V_{a0}^{-1}
\]

\[
L_g \frac{d i_{qf}^{-1}}{d t} = L_g \omega i_{af}^{-1} - R_g i_{qf}^{-1} - V_{af}^{-1} + V_{q0}^{-1}
\]

(3.17)

Since the controller for the GF system is based on a local FCS-MPC, the approach is to find one step ahead predictions of control variables [68] for each sequence component. The predictions of extracted components, which are discrete values [68], depend on measurements of the respective abc stationary frames at instant, \( K \) and rotated frames at, \( \theta = \omega t \) and \( -\omega t \). Hence extracted component models need to be discretized according to the following [71],

\[
\frac{d X}{d t} \approx \frac{X(k) - X(k - 1)}{T_s}
\]

(3.18)

where \( T_s \) is the sampling time. The state space model for positive sequence state variables associated with converter of a GF subsystem is defined as,

\[
X_{GF}^+_{af} (k+1) = A_{GF}^+ X_{GF}^+_{af} (k) + B_{GF}^+ U_{GF}^+ (k) + H_{GF}^+ W_{GF}^+ (k)
\]

(3.19)

And for negative sequence state vector,

\[
X_{GF}^-_{af} (k+1) = A_{GF}^- X_{GF}^-_{af} (k) + B_{GF}^- U_{GF}^- (k) + H_{GF}^- W_{GF}^- (k)
\]

(3.20)

The state vector \( W(k) \) is a state vector of sequence current components of output current for the converter. This vector is defined as,

\[
W_{GF}^{+1} (k) = \begin{bmatrix} i_{af}^{+1} \\ i_{qf}^{+1} \end{bmatrix}^T
\]

(3.21)
\[ W_{gf}^{-1}(k) = \begin{bmatrix} i_{d0}^{-1} & i_{q0}^{-1} \end{bmatrix}^T \] (3.22)

The main state vector for the converter is defined for sequence components as in (3.23) and (3.24),

\[ X_{gF}^{+1}(k) = \begin{bmatrix} V_{af}^{-1} & V_{qf}^{-1} & i_{df}^{-1} & i_{qf}^{-1} \end{bmatrix}^T \] (3.23)

\[ X_{gF}^{-1}(k) = \begin{bmatrix} V_{af}^{-1} & V_{qf}^{-1} & i_{df}^{-1} & i_{qf}^{-1} \end{bmatrix}^T \] (3.24)

The matrices of the discrete model, which are obtained by substituting (3.18) into (3.12), (3.13), (3.16) and (3.17), are defined as,

\[
A_{gf}^{+1} = \begin{bmatrix}
1 & \omega T_s & T_s/C_g & 0 \\
-\omega T_s & 1 & 0 & T_s/C_g \\
T_s/L_g & 0 & (1 - R_g T_s/L_g) & \omega T_s \\
0 & T_s/L_g & -\omega T_s & (1 - R_g T_s/L_g)
\end{bmatrix} \\
A_{gf}^{-1} = \begin{bmatrix}
1 & -\omega T_s & T_s/C_g & 0 \\
\omega T_s & 1 & 0 & T_s/C_g \\
T_s/L_g & 0 & (1 - R_g T_s/L_g) & -\omega T_s \\
0 & T_s/L_g & \omega T_s & (1 - R_g T_s/L_g)
\end{bmatrix} \] (3.25)

\[
B_{gf}^{+1} = \begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & T_s/L_g \\
0 & T_s/L_g
\end{bmatrix}, \quad H_{gf}^{+1} = \begin{bmatrix}
-T_s/C_g & 0 \\
0 & T_s/C_g \\
0 & 0 \\
0 & 0
\end{bmatrix}
\]

The B and H matrices have elements that are identical since it is assumed that parameters have the same value for both positive and negative sequences.
3.3.2 Design of Local FCS-MPC for GF Converter Subsystem

The model derived in the above section is employed to design the local FCS-MPC for subsystem in the microgrid that is controlled as voltage source converter. This converter sets up and controls rated voltage of the microgrid at nominal frequency [5]. The general state space model that accounts for DMPC with state and input coupling is defined as [94],

\[ X_i(k + 1) = A_iX_i(k) + B_iU_i(k) + \sum_{j \neq i} (A_{ij}X_{ij}(k) + B_{ij}U_{ij}(k)) \]  (3.26)

where M is the number of subsystems that form the overall system and i, j \( \subset M \). Comparing equation (3.26) with model obtained in (3.19) and (3.20) it is observed that the GF subsystem has no input coupling with other GFEs or even if more than one GF subsystem exists. In addition we assume that the current supplied by a DER of a GF subsystem supplies the difference between total load current and the sum of currents supplied by GFE subsystems (in a per component fashion, which is the approach adopted in this work). The latter assumption will hold as long as the GF unit has a dispatchable DER such as for example battery, storage or fuel cell packs. Therefore, the interaction matrices per positive and negative sequences are,

\[ A_{ij}^+ = [0], A_{ij}^- = [0], B_{ij}^+ = [0] \text{ and } B_{ij}^- = [0] \]  (3.27)

The FCS-MPC determines the optimum switching group that achieves minimal value of a cost function [68]. In this work, the cost function is extended to both positive and negative sequence voltage components. Hence, the switching pattern is determined as the one that minimizes differences of both sequences. An approach for voltage source
converter control suggested in [76] is used in this section with the following modifications to account for the balanced and unbalanced loading at the PCC of the microgrid:

1. The approach is modified to a per component voltage strategy, hence we will work with positive and negative sequence voltage and currents related to the controls.

2. The method of component approach is implemented in SRF and not in the $\alpha\beta$ stationary frame. This is due to the components that are essential to the controls are extracted in SRF.

The current supplied by this converter, which is required for predictions of voltage, can be estimated at instant $k-1$ and assume to hold at sampling instant $k$ [76]. In SRF, the estimation for dq current is given by [76],

$$i_{dqg}(k-1) = i_{dqf}(k-1) - \frac{C_g}{T_s} (V_{dqf}(k) - V_{dqf}(k-1)) \quad (3.28)$$

In this work, since the load current has unbalanced component which rotates at negative sequence, the current supplied by the GF subsystem has two components which need to be estimated based on positive and negative sequence capacitor voltage. Therefore, per component current estimation is defined for positive and negative sequences as,

$$i_{dqg}^{+1}(k-1) = i_{dqf}^{+1}(k-1) - \frac{C_g}{T_s} (V_{dqf}^{+1}(k) - V_{dqf}^{+1}(k-1)) \quad (3.29)$$

$$i_{dqg}^{-1}(k-1) = i_{dqf}^{-1}(k-1) - \frac{C_g}{T_s} (V_{dqf}^{-1}(k) - V_{dqf}^{-1}(k-1)) \quad (3.30)$$

The converter is controlled to produce positive voltage sequence. The steps for the control procedure are outlined as follows:
1. The state vector, $X_{GF}$ is predicted for positive and negative sequence voltage components using (3.19) and (3.20) with matrices (3.25).

2. The predicted currents are evaluated for all possible switching states [76], hence there are two vectors of one step predicted currents for positive and negative sequence components. The input to the state model, $U_{GF}(k)$ is equal to the output voltage at the converter terminals in dq axes defined for positive sequence by [117],

$$U_{GF}^+(k) = \frac{2}{3} V_{dc} \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \text{SW}$$ \hspace{1cm} (3.31)

And the input to a negative sequence prediction model is defined as,

$$U_{GF}^-(k) = \frac{2}{3} V_{dc} \begin{bmatrix} \cos(-\theta) & \sin(-\theta) \\ -\sin(-\theta) & \cos(-\theta) \end{bmatrix} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \text{SW}$$ \hspace{1cm} (3.32)

where $V_{dc}$, $\theta$ and \text{SW} are the DC voltage of the DER source, grid angle and sub-vector from matrix of possible switching configurations respectively. Grid angle detection is implemented in this work by the conventional phase locked loop (PLL) [117].

3. An additional one step ahead prediction of capacitor voltage is implemented [76]. Hence two step predictions are obtained for each sequence voltage component in dq axes. Here the second step predictions of capacitor voltage for positive and negative sequences, $V_{dqd}^{+1}(k+2)$ and $V_{dqd}^{-1}(k+2)$, are obtained.

4. A combined cost function that penalizes differences between reference voltage component of positive and negative sequences and the corresponding predicted dq voltage components. For the GF subsystem the cost function is defined as,
\[ J_{GF} = J_{Gf}^1 + J_{Gf}^3 = \left( V_{dqref}^{+1} - V_{dqf}^{+1}(k + 2) \right)^T \left( V_{dqref}^{+1} - V_{dqf}^{+1}(k + 2) \right) + \left( V_{dqref}^{-1} - V_{dqf}^{-1}(k + 2) \right)^T \left( V_{dqref}^{-1} - V_{dqf}^{-1}(k + 2) \right) \] (3.33)

The vector, \( V_{dqref} \), contains the reference setting of each dq sequence component.

The proposed method of per component control for converter of GF subsystem in the microgrid is shown in Fig. 3.2.
Figure 3.2 Block Diagram of the Proposed per Component Control Method for GF with Balanced and Unbalanced Loading
3.4 Component Based Control for a Grid Following Subsystem

These subsystems are controlled to inject controlled amount of power towards a grid [52]. In this work GFE converters are used to deliver current to loads at the PCC in a per component fashion. GFE converters are used for both grid and island modes of operation in the microgrid. For the work in this chapter, it is assumed that the supply is asymmetry and distortion free. Therefore, the unbalanced current component which is expressed as a negative sequence component is due to the unbalanced loading effect only.

3.4.1 Decomposition, Extraction and Modelling of Control Quantities for Grid Following Subsystem Converter

The quantities related to the controls of GFE are the converter output current and the PCC voltage which are the interacting states between all subsystems in the considered microgrid system. According to (3.2) and (3.3), the SRF expression of supplied current and PCC voltage are,

\[
\begin{align*}
    i_{a\beta} e^{-j\omega t} &= i_{dq}^+ + i_{dq}^- e^{-j2\omega t} \\
    i_{a\beta} e^{j\omega t} &= i_{dq}^+ e^{j2\omega t} + i_{dq}^- \\
    V_{P_{a\beta}} e^{-j\omega t} &= V_{P_{dq}}^+ + V_{P_{dq}}^- e^{-j2\omega t} \\
    V_{P_{a\beta}} e^{j\omega t} &= V_{P_{dq}}^+ e^{j2\omega t} + V_{P_{dq}}^-
\end{align*}
\]

Here \(i_{dq}\) and \(V_{P_{dq}}\) are the current supplied by a GFE subsystem and PCC voltage in dq axes. To model each current sequence, the voltage balance in space vector is,

\[
(L_f + L_i) \frac{d\vec{i}}{dt} = -(R_f + R_i)\vec{i} - \vec{V_p} + \vec{V}
\]
where $L_f/\ell, R_f/\ell$ and $\vec{V}$ are the inductance, resistance of filter/line and output terminal voltage of GFE converter respectively. In terms of sequence components, the voltage balanced for positive sequence is expressed as,

$$
(L_f + L_i) \frac{d(i_{dq}^+ e^{j\omega t})}{dt} = -(R_f + R_i)i_{dq}^+ e^{j\omega t} - V_p^+ e^{j\omega t} + V_{dq}^+ e^{j\omega t} \tag{3.37}
$$

And for negative sequence,

$$
(L_f + L_i) \frac{d(i_{dq}^- e^{-j\omega t})}{dt} = -(R_f + R_i)i_{dq}^- e^{-j\omega t} - V_p^- e^{-j\omega t} + V_{dq}^- e^{-j\omega t} \tag{3.38}
$$

Here $V_{dq}$ is the output voltage of converter for a GFE subsystem in dq-axes. Finally, the time equations for voltage balance per sequence for $d$ and $q$ axis are,

$$
(L_f + L_i) \frac{di_{d}^+}{dt} = (L_f + L_i)\omega i_{d}^+ - (R_f + R_i)i_{d}^+ - V_p^+ + V_d^+ \tag{3.39}
$$

$$
(L_f + L_i) \frac{di_{q}^+}{dt} = -(L_f + L_i)\omega i_{q}^+ - (R_f + R_i)i_{q}^+ - V_p^+ + V_q^+ \tag{3.39}
$$

$$
(L_f + L_i) \frac{di_{d}^-}{dt} = -(L_f + L_i)\omega i_{d}^+ - (R_f + R_i)i_{d}^- - V_p^- + V_d^- \tag{3.40}
$$

$$
(L_f + L_i) \frac{di_{q}^-}{dt} = (L_f + L_i)\omega i_{q}^+ - (R_f + R_i)i_{q}^- - V_p^- + V_q^- \tag{3.40}
$$

The discrete state space model for this converter per sequence component is defined as,

$$
X^+(k+1) = A^+ X^+(k) + B^+ U^+(k) + H^+ W^+(k) \tag{3.41}
$$

$$
X^-(k+1) = A^- X^-(k) + B^- U^-(k) + H^- W^-(k) \tag{3.42}
$$

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Equations (3.39) and (3.40) are discretized by substituting each derivative with (3.18) and the parameter matrices are as defined in (3.43).

\[
A^{+1} = \begin{bmatrix} 
1 - \frac{R_f + R_l}{L_f + L_l}T_s & \omega T_s \\
-\omega T_s & 1 - \frac{R_f + R_l}{L_f + L_l}T_s 
\end{bmatrix}
\]

\[
A^{-1} = \begin{bmatrix} 
1 - \frac{R_f + R_l}{L_f + L_l}T_s & -\omega T_s \\
\omega T_s & 1 - \frac{R_f + R_l}{L_f + L_l}T_s 
\end{bmatrix}
\]

\[
B^{\pm 1} = \begin{bmatrix} 
\frac{T_s}{L_f + L_l} & 0 \\
0 & \frac{T_s}{L_f + L_l} 
\end{bmatrix}, \quad H^{\pm 1} = \begin{bmatrix} 
-\frac{T_s}{L_f + L_l} & 0 \\
0 & -\frac{T_s}{L_f + L_l} 
\end{bmatrix}
\]

The state vectors for the GFE converter are,

\[
X^{+1}(k) = \begin{bmatrix} 
i_d^{+1}(k) \\
i_q^{+1}(k)
\end{bmatrix}^T
\]

\[
X^{-1}(k) = \begin{bmatrix} 
i_d^{-1}(k) \\
i_q^{-1}(k)
\end{bmatrix}^T
\]

\[
W^{+1}(k) = \begin{bmatrix} 
Vp_d^{+1}(k) \\
Vp_q^{+1}(k)
\end{bmatrix}^T
\]

\[
W^{-1}(k) = \begin{bmatrix} 
Vp_d^{-1}(k) \\
Vp_q^{-1}(k)
\end{bmatrix}^T
\]

The individual component model derived is used in the FCS-MPC for local controller of the GFE subsystem of the microgrid.
3.4.2 Proposed Local Controller for GFE Converter

The controller for this subsystem requires current component references which are obtained through SRF based decomposition and extraction of load current measured at the PCC. The main objective of local controller is to minimize the difference between reference and predicted currents [71]. By comparing the DMPC total model of the $i^{th}$ subsystem in (3.26) with the model derived for the GFE converter in (3.41) and (3.42), the following coupling matrices, for GFE subsystem $i = 1$ relative to the $j^{th}$ GFE subsystem in the considered microgrid configuration are defined,

$$A_{ij}^+ = H^+, A_{ij}^- = H^-, B_{ij}^+ = B_{ij}^- = 0$$  \hspace{1cm} (3.48)

The control for this subsystem can be summarized as follows,

1. Predictions of current components are carried by the discrete model in equations (3.41) and (3.42) with the matrices defined in equation (3.43). The dq input of the GFE converter model is the same as in (3.31) and (3.32) for positive and negative sequences, but the DC voltage used is that of the GFE DER energy source.

2. According to the share factors per sequence component, the reference values are obtained. These references are tracked by the proposed FCS-MPC. The share factors, assumed to be determined from a central controller of the microgrid, for a positive and negative sequence current component are, $SF_j^+$ and $SF_j^-$ corresponding to the $j^{th}$ GFE subsystem respectively. Therefore, If extracted sequence components of load current at the PCC are, $i_{dqL}^+$ and $i_{dqL}^-$, then the reference values of the $j^{th}$ GFE converter are,
\[ i_{dqref}^{+1} = S F_j^{+1} \begin{bmatrix} i_{dq}^{+1}(k) \\ i_{ql}^{+1}(k) \end{bmatrix}^T \]  
(3.49)

\[ i_{dqref}^{-1} = S F_j^{-1} \begin{bmatrix} i_{dq}^{-1}(k) \\ i_{ql}^{-1}(k) \end{bmatrix}^T \]  
(3.50)

3. The primary objective is to minimize the deviation from reference setting for each of the DC extracted component. Accordingly, the cost function of a GFE converter, for fundamental positive and negative sequence, is defined as,

\[ J_{GFE} = J^+ + J^- = \left( i_{dqref}^{+1} - i_{dq}(k + 1) \right)^T \left( i_{dqref}^{+1} - i_{dq}(k + 1) \right) + \left( i_{dqref}^{-1} - i_{dq}(k + 1) \right)^T \left( i_{dqref}^{-1} - i_{dq}(k + 1) \right) \]  
(3.51)

where \( i_{dq}(k + 1) \) is equal to the state vector for each sequence components. Hence the cost function is evaluated for possible switching configurations [68] and the one that achieves minimum value for positive and negative sequence current components is selected and applied to associated converter switches. Details of the proposed per component FCS-MPC of a GFE subsystem is shown in the block diagram of Fig. 3.3.

It is worth mentioning here that the DMPC for \( j^{th} \) GFE subsystem takes part in achieving the global objective of the microgrid, which is mainly to maintain reliability of supply by, collectively (with other in service GFEs), satisfy a power match between available capacity and total demand at any instant. In grid mode, participating GFEs local controllers work to achieve regulation of current components. Hence the utility grid preserves nominal frequency through the power balance in particular at times of heavy consumption.

In island mode of operation, challenges to achieve power balance is more obvious [5]. Therefore, distributed controllers’ play the same role of providing regulated current, in
per component fashion as this work is proposing. Eventually this maintains power balance and eliminate any deceleration of the microgrid system.

3.5 Decomposition and Extraction of Components for Microgrid Load Current

The load current which for this case has positive and negative sequence fundamentals. In the microgrid under study, it is assumed that the unbalanced load is

![Diagram](image-url)
represented by a three phase load that adds a fundamental component to that of the balanced portion of the load. Practical unbalancing in load could include two phase loads with unequal power consumption. This adds to the negative sequence current and will be dealt with in Chapter 4.0 of this dissertation. Decomposition which involves rotating the stationary frame \( abc \) load current at \( \theta = \omega t \) and \( \theta = -\omega t \) to obtain \( dq \) axes current of both sequences. Figure 3.4 shows a block diagram of the decomposition and extraction of components.

![Block Diagram of Load Current Decomposition and Extraction Based on SRF](image)

### 3.6 Simulation and Results

The microgrid system in Fig. 3.1 is simulated in both grid and island modes. In grid mode, the proposed per component FCS-MPC approach is tested with high and low short circuit levels, that is, strong and weak utility grid condition. Parameters of the system under study are given in Table 3.1. In this chapter the microgrid system under study is assumed to have two GFE subsystems (in grid and island mode) and one GF subsystem.
### Table 3.1 Parameters of Microgrid System

<table>
<thead>
<tr>
<th>DER voltage, GF(E), (V_{DC})</th>
<th>800 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal (V) and (f)</td>
<td>208 (L-L) V, 60 Hz</td>
</tr>
<tr>
<td>(C_g)</td>
<td>350 µF</td>
</tr>
<tr>
<td>(R_{g,L})</td>
<td>0.0754 Ω, 2 mH.</td>
</tr>
<tr>
<td>(R_{f_k,L_{f_k}}) for (k = 1,2)</td>
<td>0.0754 Ω, 10 mH.</td>
</tr>
<tr>
<td>(R_{l,L})</td>
<td>0.75 Ω, 1 mH.</td>
</tr>
<tr>
<td>(R_{c_l,L_{c_l}})</td>
<td>1.2 Ω, 1 mH</td>
</tr>
<tr>
<td>(R_{G,L}) strong/weak</td>
<td>0.001 Ω, 10 µH [105]/1.2 Ω, 1 mH</td>
</tr>
<tr>
<td>Balanced load</td>
<td>(S_a = 3 + j0.8, S_b = 1 + j2) and (S_c = 0.1 + j0.4) KVA</td>
</tr>
<tr>
<td>Unbalanced load</td>
<td>(S_a = 3 + j0.8, S_b = 1 + j2) and (S_c = 0.1 + j0.4) KVA</td>
</tr>
</tbody>
</table>

#### 3.6.1 Validation of Synchrouns Reference Frames Based Decomposition and Extraction for PCC Voltage and Load Current

In this first case, the performance of the decomposition SRF is validated for both modes of microgrid operation. The balanced and unbalanced loads are switched at \(t = 0.05\) and 0.2 sec. respectively. For this particular case, a strong utility grid is assumed. Figure 3.5 (a)- (b) shows decomposition of microgrid PCC voltage. It is observed that if the grid has a very low impedance, then the negative sequence voltage drop which is, \(i_{dq}^{-1}(R_t + jX_t)\) is of negligible amount. Therefore, the PCC voltage is balanced and free from any negative sequence component. Also the positive sequence voltage component prior to filtering has no significant ripple since the magnitude of the negative sequence \(V_{P_{dq}^{-1}}\), which rotates at double the nominal frequency has no significant effect. Load current of the PCC which is also decomposed by the SRF is shown before and after filtering in Fig. 3.6 (a)- (b). In Fig. 3.6 (a), the positive and negative dq currents have components \(i_{dq}^{-1}\) and \(i_{dq}^{+1}\) that rotates at \(2\omega\) respectively. Post filtering currents of Fig. 3.6 (b), are the extracted DC components that will be used in the control algorithm of GFE.
converters. Also, it is observed that the positive sequence endures less ripple because of the loading conditions $i_{dq}^{+1} > i_{dq}^{-1}$. To validate the decomposition for an island mode of operation, the grid is replaced with a GF converter. Figure 3.7 depicts the PCC voltage pre/post filtering. Here, the negative sequence voltage has a magnitude since the connecting line has an impedance which produces significant $i_{dq}^{-1}(R_l + jX_l)$. The PCC current which is supplied by GF converter is shown in Fig. 3.8. Results show the SRF method capability of decomposing and extracting for both grid and island modes of microgrid operation.
Figure 3.5 PCC Voltage in SRF (a) Unfiltered and (b) Filtered Components for Strong Grid Case
Figure 3.6 PCC Load Current in SRF (a) Unfiltered and (b) Filtered Components for Strong Grid Case
Figure 3.7 PCC Voltage in SRF (a) Unfiltered and (b) Filtered Components for Island Mode/GF Converter
Figure 3.8 PCC Load Current in SRF (a) Unfiltered and (b) Filtered Components for Island Mode/GF Converter
3.6.2 Component Control Based on Local FCS-MPC for Grid Mode Operation

In this section, GFE converters are switched ON to deliver a specified current in a per component fashion. Each subsystem has its associated controller. The components controlled are fundamental positive and negative sequence which corresponds to the combined balanced and unbalanced loads at the PCC. Two grid conditions are considered with impedances given in Table 3.1. Figures 3.9 and 3.10 depict current tracking for GFE1 and GFE2 subsystems respectively which are simultaneously switched at $t = 0.5 \text{ sec}$. Share factors for positive sequence components are, $SF_1^{+1} = 0.5, SF_2^{+1} = 0.25$ whereas negative sequence components shares are, $SF_1^{-1} = 0.25, SF_2^{-1} = 0$. Results verify that per component approach proposed here yields feasible tracking behavior for each sequence component per GFE subsystem. The results recorded here is based on a quality factor of 4 for the notch filters which eliminate the double frequency ripple embedded in the DC components.

The grid current for this case is shown in Fig. 3.11. It is seen that the grid contribution decreases significantly due to the oncoming microgrid units. Here, from a distributed MPC perspective, the grid serves to maintain global objective of controlling voltage and frequency, whereas the microgrid units share the load on a per component approach to satisfy the power balance and implicitly contribute to preserve the global objective. One observation from Fig.3.11 is that the grid current suffers a considerable imbalance. This is due to the fact that only 25% of negative sequence current is supplied by the microgrid (only GFE1) and 75% is supplied by the grid itself. Figure 3.12 depicts the amount of negative sequence current content in grid current.
Figure 3.9 Current Tracking of Local FCS-MPC for GFE1 Subsystem

Figure 3.10 Current Tracking of Local FCS-MPC for GFE2 Subsystem with Zero Negative Sequence Share
Figure 3.11 Utility Grid Current with GFE2 Supplying Zero Negative Sequence Current

Figure 3.12 Negative Sequence Content in Current Supplied by Grid with Zero GFE2 Share of $i_{dq2}^{-1}$
The PCC voltage for this case is shown in Fig. 3.13. It is seen that because the grid has a negligible impedance, no negative sequence voltage content is traced and hence balanced symmetrical waveforms are observed. Also due to the strong grid condition, no harmonic content from the GFEs converter penetrated the PCC [118]. To better balance the grid current, the share of GFE2 from negative sequence current is increased from zero to 30%. Therefore, 55% of the negative sequence current is collectively shared by GFE1 and GFE2. Figure 3.14 shows GFE2 negative sequence tracking only whereas Fig. 3.15 depicts the grid current where a highly balanced tendency is obtained. Figure 3.16 shows the negative sequence current content. Here the contribution of GFE2 share is evident.

![Figure 3.13 PCC Voltage for a High Short Circuit Level Utility Grid](image)
**Figure 3.14** Negative Sequence Current Tracking for GFE2 with a 30% Share of $i_{dq2}^{-1}$

**Figure 3.15** Utility Grid Current with GFE2 Supplying 30% Negative Sequence Current

**Figure 3.16** Negative Sequence Content in Grid Current with 30% GFE2 Share of $i_{dq2}^{-1}$
In the remaining part of this section the proposed distributed FCS-MPC with a per component approach is tested on a low KVA short circuit. Impedance for utility grid corresponding to this case is shown in Table 3.1. Two objectives are pursued here. The first is to examine how well the decomposition of the SRF performs for this type of condition that are commonly encountered in distribution systems. Secondly, a validation of the distributed FCS-MPC is examined to evaluate components regulation for this case. Figure 3.17, shows tracking of GFE1 current sequence components with share factors defined as, $SF_1^{+1} = 0.5, SF_2^{+1} = 0.25$ and for negative sequence as $SF_1^{-1} = 0.25, SF_2^{-1} = 0.3$. The proposed method and controller shows satisfactory performance even when a weak utility grid is encountered. Hence this confirms the feasibility of the method under different grid conditions. Figures 3.18 and 3.19 depicts tracking performance of GFE2 and the current supplied by the utility grid in abc stationary frame respectively. The PCC voltage for the weak grid condition is shown in Fig 3.20. Here as the grid has a low short circuit KVA and harmonics content from GFE converters penetrate into PCC [118]. Negative sequence profile in the PCC voltage is shown in Fig. 3.21. If the negative content is defined relative to the positive sequence voltage of the PCC, then the UVF is [119],

$$UVF = \frac{V_p^{-1}}{V_p^{+1}} \times 100\% \quad (3.52)$$
Figure 3.17 Current Tracking of Local FCS-MPC for GFE1 Subsystem under Weak Utility Grid

Figure 3.18 Current Tracking of Local FCS-MPC for GFE2 Subsystem under Weak Utility Grid
Figure 3.19 Utility Grid Supplied Current under Low Short Circuit KVA

Figure 3.20 Voltage at PCC under a Low Short Circuit Level Utility Grid Mode of Operation
It is worth mentioning here that the positive sequence PCC voltage, $V_{p}^{+1}$, used in (3.52) is based on the value determined from simulation. Prior to switching of GFE converters a large drop in voltage is caused by the situation that utility grid supplies all current. However, after switching of microgrid units, the voltage profile at the PCC is boosted since the grid now supplies about only 25% of the load current. Hence, the base value for calculation of UVF is dependent on the time interval that reflect switching/non-switching of GFE converters.

3.6.3 Component Control Based on Local FCS-MPC for an Islanded Microgrid

In this part of the validation, an island condition is considered. In this case the main switch in Fig.3.1 is opened and only one GF converter is used, hence $n = 1$. Due to the absence of utility grid, a GF converter is used to setup the voltage [5]. The other two converters are operated as GFEs that inject per component load current. The first step in
the validation process for an island case is to examine the performance of GF converter in setting up the nominal positive sequence voltage. Two objectives are pursued from this first step. The first is evaluation of tracking performance and the second, is the evaluation of the robustness where the reference setting is subjected to an increase/decrease and tracking response is again evaluated. Figure 3.22 shows tracking of capacitor voltage in abc frame. Very good tracking performance is observed for positive sequence voltage whereas negative sequence voltage is attained to zero through the local FCS-MPC. To investigate robustness to changes in reference values, a two-step change profile is shown in Fig 3.23 (a) and the corresponding controller response is observed in Fig. 3.23 (b). The response proves the ability of the controller to follow the new reference setting rapidly following an increase/decrease step alteration. It also confirms that the cost function defined by (3.33) is able to determine a switching pattern that minimizes the differences between predicted positive and negative sequence voltage components from the desired reference values. For the negative sequence component, this reference is zero.
Figure 3.22 Voltage Tracking of the per Component FCS-MPC for GF Converter Subsystem
At this point the performance of other local subsystem controllers for island mode are evaluated. The two GFE converters are switched at $t = 0.5 \text{ sec.}$, and share factors for this case are, $SF_1^{+1} = 0.5, SF_2^{+1} = 0.4$ and for negative sequence component, $SF_1^{-1} = 0.4, SF_2^{-1} = 0.4$. Tracking performance is shown for GFE1 and GFE2 in Figs. 3.24 and 3.25 respectively. The proposed method show that the per component FCS-MPC enables regulation of each component towards the desired value. Here the two GFEs supply collectively a positive sequence of 90% and 80% of negative sequence load currents. Therefore, the current supplied by the GF converter is considerably decreased. This current is shown in Fig. 3.26 with tendency towards a balanced profile due the fact that this converter supplies only 20% of the negative sequence current due the unbalanced load. A
study of the PCC waveform in Fig. 3.27 reveals that an almost negative sequence free profile is obtained despite the negative sequence drop $i_{dgy}^{-1}Z_t$. This is due to the cost function of the local FCS-MPC for the GF subsystem that regulates negative sequence voltage across the filtering capacitor to zero and the decreased negative sequence current delivered by the converter. The latter is due to the large share factors of the GFE converters.

The negative sequence profile for the PCC voltage is shown in Fig. 3.28. It is worth mentioning here that the overall voltage drop (due to positive and negative sequence currents supplied by GF converter) undergoes a considerable decrease. Therefore at $= 0.5 \text{ sec.}$, a loop that reduces the positive sequence reference setting of the GF capacitor voltage is implemented to maintain the nominal value of the PCC voltage.

Figure 3.24 Tracking Performance of GFE1 FCS-MPC for Island Mode Operation
Figure 3.25 Tracking Performance of GFE2 FCS-MPC for Island Mode Operation

Figure 3.26 Current Delivered by GF Subsystem
Figure 3.27 Voltage at PCC During Island Mode with GFEs Supplying 80% of the Negative Sequence Current Component

Figure 3.28 Negative Sequence Content of Microgrid PCC Voltage under Island Mode
3.6.4 Verification of Decoupled Input for DMPC of Microgrid Subsystems

In (3.27) and (3.48) the matrices $B_{ji}^+ \text{ and } B_{ji}^-$ are of zero elements and accordingly no input interaction between microgrid subsystems exists. However, at this point it is vital to investigate that any change in subsystem $i$ does not have an effect on the other subsystems. In this aspect, the following question is asked, does a change in a share factor (per sequence component) of a GFE has any effect on the inputs, $U^{+1}(k) \text{ and } U^{-1}(k)$ for other switched GFEs? Or even a GF subsystem? When an island mode is in force. For this purpose, the total number of commutations of converter switches is employed to evaluate input decoupling. Hence the question becomes, for a change of share factors initiated in subsystem GFE2, by how much (if any) will the average number of commutations (during a specified simulation time) in subsystem GFE1 or GF changes? In this case an island mode is considered. In some literature on FCS-MPC, the number of commutations which represents the difference in switching pattern between $k+1 \text{ and } k$ instants is incorporated in the cost function as a weighted term to control switching frequency [120],[79]. The number of commutation changes is defined in [120] and here it is expressed in terms of a sample of simulation interval for phase $\lambda$ as,

$$C_{x\lambda} = \sum_{t_1}^{t_2} |S_{opt\lambda}(k+1) - S_{opt\lambda}(k)|, \forall x \text{ is } GF, GFE_1 \text{ or } GFE_2$$

where $t_1$ is the start of the simulation interval, $t_2$ is the end of the considered simulation interval and $S_{opt\lambda}$ is optimum switching pattern of the phase under consideration found from minimizing the local FCS-MPC composite cost function. Hence the average number
of commutations for an $X$ type subsystem, two level topology, converter in the microgrid is given by,

$$ C_{avg} = \left( \sum_{\lambda=1}^{3} C_{\lambda} \right) / 3 \quad (3.54) $$

The factor $C_{avg}$ is calculated for each converter for two different cases of share factors. In the first case, GFE2 supplies no negative sequence current and in the second GFE2 supplies a share of this component. Table (3.2) below summarizes values of $C_{avg}$ for all three converters in the microgrid. Data of Table (3.2) is based on share factors given in Section 3.6.2 of this chapter.

<table>
<thead>
<tr>
<th>Case #</th>
<th>$C_{avg \ GF}$</th>
<th>$C_{avg \ GFE1}$</th>
<th>$C_{avg \ GFE2}$</th>
<th>$% C_{avg \ GF}$</th>
<th>$% C_{avg \ GFE1}$</th>
<th>$% C_{avg \ GFE2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12774</td>
<td>1772</td>
<td>1878</td>
<td>0.0625 %</td>
<td>0.894 %</td>
<td>3.741 %</td>
</tr>
<tr>
<td>2</td>
<td>12782</td>
<td>1788</td>
<td>1951</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results verify that each subsystem has inputs that are not decoupled in anyway, because a change in share factors for a subsystem induces a negligible alteration in the number of commutation in other subsystems. Hence, these subsystems have no effect on each other despite the fact that they are all connected to a common PCC. Also, as long as GFE subsystems satisfy regulation of current components then they participate in the global objective of maintaining nominal frequency through a demand/capacity match.
3.7 Summary

In this chapter the proposed per component FCS-MPC is presented for a microgrid conditions that include balanced and unbalanced loading. Two components are included in the cost function of a local subsystem: positive and negative sequence at the fundamental frequency. Results prove the ability of the SRF to decompose voltages and current at steady state which are associated with the control approach. The proposed per component control is tested under different modes that include grid and island modes. In addition, two utility grid conditions are considered in the validation. Each distributed FCS-MPC is subjected to a change either reference setting or share factors and robustness are evaluated.
4.1 Introduction

Microgrids, which are part of electric power system, have loading conditions that resemble those of a conventional distribution networks. Loads could be unbalanced between phases and can also operate as two phase. In addition several consumer apparatus and some industrial loads present a non-linear behavior that that could setup current components that reflect harmonic consumption. In this chapter per component control approach is proposed, which is based on distributed finite control set-model predictive control to a microgrid system that has:

1. A non-linear load that is represented by a six pulse uncontrolled AC/DC converter, this load has 5th, 11th, 17th harmonic rotated in negative sequence, whereas 7th, 13th, 19th have positive sequence rotation [121].

2. An increased degree of unbalanced loading achieved by connecting two phase loads that are clustered at the PCC.

The emphasis is to propose, model and validate a multi-component FCS-MPC control approach of power converters that interface DERs in the microgrid system.
4.2 Multiple Synchronous Reference Frames Decomposition of Relevant Microgrid Control Quantities

In the previous chapter SRF was employed to decompose and extract voltages and currents components at steady state. Quantities were expressed using positive and negative sequences, hence a double SRF [109] approach is necessary. In this chapter however, the SRF is extended to multiple frames [110]. Due to island and grid modes voltage and current quantities must be decomposed. Here the number of frames are equal to the components that are incorporated in the controls. The system considered in this chapter is the same as that of chapter 3.0 but with modified loading conditions as depicted in Fig. 4.1. For this case, voltage and current of a microgrid subsystem or PCC, contains fundamental and harmonic components of positive or negative sequence. Given an \( X \) quantity, a \( 6h_1 + 1 \) and \( 6h_2 - 1 \) components rotate in positive and negative sequences respectively. Hence from the stationary \( \alpha \beta \) to \( dq \), this quantity is expressed as,

\[
X_{\alpha \beta} = X_{dq}^{+1} e^{j\omega t} + X_{dq}^{-1} e^{-j\omega t} + \sum_{h_1=0}^{\infty} X_{dq}^{(6h_1+1)} e^{j(6h_1+1)\omega t} + \sum_{h_2=1}^{\infty} X_{dq}^{-(6h_2-1)} e^{-j(6h_2-1)\omega t} + X^0 \tag{4.1}
\]

The goal here is to extract a voltage or current component that could be a positive or negative fundamental or harmonic component. Hence a targeted positive and negative sequence component is denoted as \( m_1 \) and \( m_2 \) respectively. Therefore, \( m_1 \in 6h_1 + 1 \) and \( m_2 \in 6h_2 - 1 \). To extract an \( m_1 \) and \( m_2 \) component, (4.1), is multiplied by \( e^{-jm_1\omega t} \) and \( e^{jm_2\omega t} \) separately to give (4.2) and (4.3),
Figure 4.1 Phase Schematic of an n GF by a k GFE Subsystem Microgrid with a Variety of Loading Conditions under Study

\[ X_{\alpha\beta}e^{-jm_1\omega t} = X_{dq}^{+1}e^{j(1+m_1)\omega t} + X_{dq}^{-1}e^{-j(1-m_1)\omega t} + \sum_{h_1=1}^{\infty} X_{dq}^{+(6h_1+1)}e^{j(6h_1+1-m_1)\omega t} + \sum_{h_2=1}^{\infty} X_{dq}^{-(6h_2-1)}e^{-j(6h_2-1+m_2)\omega t} \]  
\[ (4.2) \]

\[ X_{\alpha\beta}e^{jm_2\omega t} = X_{dq}^{+1}e^{j(1+m_2)\omega t} + X_{dq}^{-1}e^{-j(1-m_2)\omega t} + \sum_{h_1=1}^{\infty} X_{dq}^{+(6h_1+1)}e^{j(6h_1+1+m_2)\omega t} + \sum_{h_2=1}^{\infty} X_{dq}^{-(6h_2-1)}e^{-j(6h_2-1-m_2)\omega t} \]  
\[ (4.3) \]
Here $X_{dq}^{\pm 1}$ is the combined fundamental component due to linear and non-linear loads. The next step is to express all quantities, which are relevant to the converter control, in terms of multiple SRF. Components considered in the controls will be limited to 5th negative and 7th positive sequence components in addition to the fundamental positive and negative sequences. Therefore, $h_1 = h_2 = 0.1$ and accordingly, $m_1 = 1.7$ and $m_2 = 1.5$. Hence, with the aforementioned values the total load current, $n^{th}$ GF subsystem output current, $k^{th}$ GFE output currents and PCC voltage, are expressed as (subscript $n$ and $k$ are dropped for simplicity),

\begin{align*}
\text{Load Current:} & \quad i_{a_L} & = i_{d_L}^{+1} + i_{dq}^{-1}e^{-j2\omega t} + i_{dq}^{+7}e^{j6\omega t} + i_{dqL}^{+5}e^{-j6\omega t} \\
& = i_{d_L}^{+1}e^{-j\omega t} + i_{dq}^{-1}e^{-j2\omega t} + i_{dq}^{+7}e^{j8\omega t} + i_{dqL}^{+5}e^{-j12\omega t} \\
& = i_{d_L}^{+1}e^{j2\omega t} + i_{dq}^{-1}e^{j\omega t} + i_{dq}^{+7}e^{j4\omega t} + i_{dqL}^{+5}e^{j12\omega t} + i_{dq}
\end{align*}

\begin{align*}
\text{GF Subsystem:} & \quad i_{a_L} & = i_{d_L}^{+1} + i_{dq}^{-1}e^{-j2\omega t} + i_{dq}^{+7}e^{j6\omega t} + i_{dqL}^{+5}e^{-j6\omega t} \\
& = i_{d_L}^{+1}e^{-j\omega t} + i_{dq}^{-1}e^{-j2\omega t} + i_{dq}^{+7}e^{j8\omega t} + i_{dqL}^{+5}e^{-j12\omega t} \\
& = i_{d_L}^{+1}e^{j2\omega t} + i_{dq}^{-1}e^{j\omega t} + i_{dq}^{+7}e^{j4\omega t} + i_{dqL}^{+5}e^{j12\omega t} + i_{dq}
\end{align*}

\begin{align*}
\text{GFE subsystem:} & \quad i_{a_L} & = i_{d_L}^{+1} + i_{dq}^{-1}e^{-j2\omega t} + i_{dq}^{+7}e^{j6\omega t} + i_{dqL}^{+5}e^{-j6\omega t} \\
& = i_{d_L}^{+1}e^{-j\omega t} + i_{dq}^{-1}e^{-j2\omega t} + i_{dq}^{+7}e^{j8\omega t} + i_{dqL}^{+5}e^{-j12\omega t} \\
& = i_{d_L}^{+1}e^{j2\omega t} + i_{dq}^{-1}e^{j\omega t} + i_{dq}^{+7}e^{j4\omega t} + i_{dqL}^{+5}e^{j12\omega t} + i_{dq}
\end{align*}
PCC voltage:

\[
V_{p\alpha\beta} e^{-j\omega t} = V_{p_{dq}^+} + V_{p_{dq}^-} e^{-j2\omega t} + V_{p_{dq}^7} e^{j6\omega t} + V_{p_{dq}^5} e^{-j6\omega t}
\]

\[
V_{p\alpha\beta} e^{-j7\omega t} = V_{p_{dq}^{1}} + V_{p_{dq}^{-1}} e^{-j6\omega t} + V_{p_{dq}^{7}} + V_{p_{dq}^{5}} e^{-j12\omega t}
\]

\[
V_{p\alpha\beta} e^{j\omega t} = V_{p_{dq}^{1}} e^{j2\omega t} + V_{p_{dq}^{-1}} + V_{p_{dq}^{7}} e^{j8\omega t} + V_{p_{dq}^{5}} e^{j4\omega t}
\]

\[
V_{p\alpha\beta} e^{j5\omega t} = V_{p_{dq}^{1}} e^{j6\omega t} + V_{p_{dq}^{-1}} e^{j4\omega t} + V_{p_{dq}^{7}} e^{j12\omega t} + V_{p_{dq}^{5}}
\]

Here \(i_{\alpha\beta L(\text{dq}L)}, i_{\alpha\beta g(\text{dq}g)}, i_{\alpha\beta (\text{dq})}\) and \(V_{p\alpha\beta (\text{dq})}\) are the output current of \(n^{\text{th}}\) GF, \(k^{\text{th}}\) GFE subsystems and PCC voltage in stationary (SRF) coordinates respectively. In order to extract a fundamental or harmonic dq component of positive or negative sequence a multi-notch filter is used. The multi-notch filter is built from a cascaded connection of single notches [115] with a unilateral bandwidth [122]. As an example, if the fundamental positive sequence is to be extracted, a filter with notches at \(2\omega\) and \(6\omega\) is employed. A low pass filter is used to limit the spectrum of each quantity so as to be consistent with the considered values of \(h1\) and \(h2\).

To illustrate an example of the decomposition for the considered microgrid, the load current and voltage at PCC, expressed by (4.4) and (4.7), are separated into components which are expressed in dq axes. Figure 4.2, shows components with embedded AC components, rotating at different frequencies, and extracted DC components. Decomposition and extraction of PCC voltage are shown in Fig. 4.3 for pre/post notch filtering. In this example, the two phase and non-linear loads details are given in Table 4.1.

| \(L_1\) (\(a & b\)) | 0.4 + \(j\)0.3 KVA |
| \(L_2\) (\(b & c\)) | 0.1 + \(j\)0.1 KVA |
| \(\text{Non-linear load}\) | \(R_L = 8\ \Omega, L_L = 40\ \text{mH}\) |
Figure 4.2 Load Current Decomposition and Extraction by Multi-SRF under Stiff Grid Mode of Operation, (a) Positive Sequence with Ripples, (b) DC Components, (c) Negative Sequence with Ripples and (d) DC Components

Figure 4.3 PCC Voltage Decomposition and Extraction by Multi-SRF under Stiff Grid Mode of Operation, (a) Positive Sequence with Ripples, (b) DC Components, (c) Negative Sequence with Ripples and (d) DC Components
The decomposition and extraction examples are carried under two different modes such that the load current is decomposed for a high short circuit KVA utility grid condition while the PCC voltage is carried out for an island mode with a GF converter subsystem. Here it is observed that the $q$ axis component of load current suffers some ripple but $d$-axis components suffer no observed oscillations. Ripple is observed also in the PCC voltage which is due to the switching effect of the converter. These components whether current or voltage will be used in the development of the per component control of power converters based on the distributed FCS-MPC.

### 4.2.1 Example of Decomposition under Linear and Non-linear Loading

In this section a numerical example is considered of the SRF decomposition with a nonlinear load. A balanced load with total power of $S = 9 + j6 \text{ KVA}$, unbalanced load of $S_a = 3 + j0.8, S_b = 1 + j2$ and $S_c = 0.1 + j0.4 \text{ KVA}$ and a six pulse converter with load $R_L = 5 \, \Omega, L_L = 8 \, \text{mH}$. For a high short circuit level grid, the instantaneous currents in dq-axis for positive sequence current are found to be: is connected across the PCC,

\[
\begin{align*}
    i_{d(t)}^+ &= 121.8 - 13.96 \cos(2\omega t + \phi_1) + 12.5 \cos(6\omega t + \phi_5) - 8.088 \cos(6\omega t + \phi_7) \\
    i_{q(t)}^+ &= -28.37 + 4.587 \sin(2\omega t + \phi_1) + 2.652 \sin(6\omega t + \phi_5) + 1.148 \sin(6\omega t + \phi_7) \\
    i_{d(t)}^7 &= -8.088 + 121.8 \cos(6\omega t + \phi_0) - 13.96 \cos(8\omega t + \phi_1) + 12.5 \cos(12\omega t + \phi_5) \\
    i_{q(t)}^7 &= 1.148 - 28.37 \sin(6\omega t + \phi_0) + 4.587 \sin(8\omega t + \phi_1) + 2.652 \sin(12\omega t + \phi_5)
\end{align*}
\]
For the negative sequence current components,

$$i_{d(t)}^{-1} = -13.96 + 121.8 \cos(2\omega t + \phi_o) + 12.5 \cos(4\omega t + \phi_5) - 8.088 \cos(8\omega t + \phi_7)$$

$$i_{q(t)}^{-1} = 4.587 - 28.37 \sin(2\omega t + \phi_o) + 2.652 \sin(4\omega t + \phi_5) + 1.148 \sin(8\omega t + \phi_7)$$

$$i_{d(t)}^{-5} = 12.5 + 121.8 \cos(6\omega t + \phi_o) - 13.96 \cos(4\omega t + \phi_1) - 8.088 \cos(12\omega t + \phi_7)$$

$$i_{q(t)}^{-5} = 2.652 - 28.37 \sin(6\omega t + \phi_o) + 4.587 \sin(4\omega t + \phi_1) + 1.148 \sin(12\omega t + \phi_7)$$

PCC voltage components for positive and negative sequence which corresponds to the high short circuit KVA are,

$$V_{d}^{+1} = 169.5 \, V, \, V_{q}^{+1} = -0.4017 \, V, \, V_{d}^{-7} = 0.05488 \, V \, \text{and} \, \, V_{q}^{-7} = 0.2097 \, V$$

Voltage negative sequence components are,

$$V_{d}^{-1} = 0.01092 \, V, \, V_{q}^{-1} = -0.06188 \, V, \, V_{d}^{-5} = -0.08163 \, V \, \text{and} \, V_{q}^{-5} = 0.2288 \, V$$

Here all sequence voltage components, except the fundamental positive, are very low this is due to the corresponding fundamental and harmonic voltage drops. If a weak grid is considered with a high Thevenin’s impedance, the current decompositions for positive sequence are,

$$i_{d(t)}^{+1} = 61.76 - 3.831 \cos(2\omega t + \phi_1) + 2.459 \cos(6\omega t + \phi_5) - 0.8618 \cos(6\omega t + \phi_7)$$

$$i_{q(t)}^{+1} = -18.54 + 1.274 \sin(2\omega t + \phi_1) + 2.724 \sin(6\omega t + \phi_5) + 1.607 \sin(6\omega t + \phi_7)$$

$$i_{d(t)}^{+7} = -0.8618 + 61.76 \cos(6\omega t + \phi_o) - 3.831 \cos(8\omega t + \phi_1) + 2.459 \cos(12\omega t + \phi_5)$$
\[ i_{q(t)}^{+7} = 1.607 - 18.54 \sin(6\omega t + \phi_o) + 1.274 \sin(8\omega t + \phi_1) + 2.724 \sin(12\omega t + \phi_5) \]

Negative sequence current components are,

\[ i_{d(t)}^{-1} = -3.831 + 61.76 \cos(2\omega t + \phi_o) + 2.459 \cos(4\omega t + \phi_1) - 0.8618 \cos(8\omega t + \phi_7) \]

\[ i_{q(t)}^{-1} = 1.274 - 18.54 \sin(2\omega t + \phi_o) + 2.724 \sin(4\omega t + \phi_1) + 1.607 \sin(8\omega t + \phi_7) \]

\[ i_{d(t)}^{-5} = 2.459 + 61.76 \cos(6\omega t + \phi_o) - 3.831 \cos(4\omega t + \phi_1) - 0.8618 \cos(12\omega t + \phi_7) \]

\[ i_{q(t)}^{-5} = 2.724 - 18.54 \sin(6\omega t + \phi_o) + 1.274 \sin(4\omega t + \phi_1) + 1.607 \sin(12\omega t + \phi_7) \]

As for the PCC voltage decomposition, positive and negative sequence components are expressed as follows (phase angle not added in expression for simplicity):

\[ v_{d(t)}^{+1} = 88.53 - 4.129 \cos 2\omega t - 8.216 \cos 6\omega t - 5.361 \cos 6\omega t \]

\[ v_{q(t)}^{+1} = -0.9769 - 2.977 \sin 2\omega t + 1.215 \sin 6\omega t + 0.1741 \sin 6\omega t \]

\[ v_{d(t)}^{+7} = 5.361 + 88.53 \cos 6\omega t + 4.129 \cos 8\omega t - 8.216 \cos 12\omega t \]

\[ v_{q(t)}^{+7} = 0.1741 - 0.9769 \sin 6\omega t - 2.977 \sin 8\omega t + 1.215 \sin 12\omega t \]

\[ v_{d(t)}^{-1} = 4.129 + 88.53 \cos 2\omega t - 8.216 \cos 4\omega t + 5.361 \cos 8\omega t \]

\[ v_{q(t)}^{-1} = -2.977 - 0.9769 \sin 2\omega t + 1.215 \sin 4\omega t + 0.1741 \sin 8\omega t \]

\[ v_{d(t)}^{-5} = -8.216 + 88.53 \cos 6\omega t + 4.129 \cos 4\omega t + 5.361 \cos 12\omega t \]
\[ v_{q(t)}^5 = 1.215 - 0.9769 \sin 6\omega t - 2.977 \sin 4\omega t + 0.1741 \sin 12\omega t \]

4.3 Multiple Component Based Control for a Grid Forming Subsystems

As stated these subsystems, used in island mode, will be controlled in order regulate positive sequence voltage component at the PCC. Through a proposed per component voltage strategy control of the filter capacitor associated with the GF converter, the PCC voltage is indirectly regulated to nominal value.

4.3.1 Mathematical Modeling of Components for Grid Forming Converter

This converter establishes the nominal voltage when the microgrid is in island mode [5]. The current balance in terms of space vector is given by [116],

\[ C_g \frac{d\vec{V}_f}{dt} = \vec{i}_f - \vec{i}_g \tag{4.8} \]

Since per component voltage control is being proposed, each component, belonging to a fundamental or harmonic, positive or negative sequence group, is modeled in time domain and is then discretized. Subsequently the model is used for providing predictions [68] for GF local FCS-MPC per each voltage component. The positive sequence current balance, in terms of extracted voltage and current components, is given by,

\[ C_g \frac{d(V_{dqf}^+ e^{j\omega t})}{dt} = i_{dqf}^{+1} e^{j\omega t} - i_{dqg}^{+1} e^{j\omega t} \tag{4.9} \]

\[ C_g \frac{d(V_{dqf}^7 e^{j7\omega t})}{dt} = i_{dqf}^{+7} e^{j7\omega t} - i_{dqg}^{+7} e^{j7\omega t} \]

And for negative sequence current balance,
\[
C_g \frac{d(V_{dqf}^+ e^{-j\omega t})}{dt} = i_{dqf}^+ e^{-j\omega t} - i_{dqw} e^{-j\omega t}
\]

\[
C_g \frac{d(V_{dqf}^- e^{-j\omega t})}{dt} = i_{dqf}^- e^{-j\omega t} - i_{dqw} e^{-j\omega t}
\]

Solving for the derivative and with some simplifications, an expression for the rate of change of an \(m_1\) and an \(m_2\) voltage component across a GF subsystem capacitor is,

\[
C_g \frac{dV_{af}^{+m_1}}{dt} = C_g m_1 \omega V_{af}^{+m_1} + i_{dafa}^{+m_1} - i_{af}^{+m_1}
\]

\[
C_g \frac{dV_{af}^{+m_1}}{dt} = -C_g m_1 \omega V_{af}^{+m_1} + i_{af}^{+m_1} - i_{af}^{+m_1}
\]

\[
C_g \frac{dV_{af}^{-m_2}}{dt} = -C_g m_2 \omega V_{af}^{-m_2} + i_{dafa}^{-m_2} - i_{af}^{-m_2}
\]

\[
C_g \frac{dV_{af}^{-m_2}}{dt} = C_g m_2 \omega V_{af}^{-m_2} + i_{dafa}^{-m_2} - i_{af}^{-m_2}
\]

It is worth mentioning that for \(m_1 = 1\), voltage and current quantities represent all the fundamental positive sequence that is due to linear and non-linear loading effects. The last part of the modelling is related to the voltage balance for the filter of the GF converter.

In terms of \(m_1\) and \(m_2\), voltage balance is expressed as,

\[
L_g \frac{d(i_{dafa}^{+m_1}) e^{j\omega_{1}\omega t}}{dt} = -j m_1 \omega L_g i_{dafa}^{+m_1} e^{j\omega_{1}\omega t} - R_g i_{dafa}^{+m_1} e^{j\omega_{1}\omega t} - V_{aq}^{+m_1} e^{j\omega_{1}\omega t}
\]

\[
L_g \frac{d(i_{dafa}^{-m_2}) e^{-j\omega_{2}\omega t}}{dt} = j m_2 \omega L_g i_{dafa}^{-m_2} e^{-j\omega_{2}\omega t} - R_g i_{dafa}^{-m_2} e^{-j\omega_{2}\omega t} - V_{aq}^{-m_2} e^{-j\omega_{2}\omega t}
\]
where $V_{dqO}$ is the output voltage of this converter corresponding to the considered voltage component. Here $V_{dqO}$ is function of the switching pattern. Finally on a per axis bases, the positive and negative sequence filter current components are,

$$
L_g \frac{d{i}_{df}^{m1}}{dt} = L_g m_1 \omega i_{qf}^{m1} - R_g i_{df}^{m1} - V_{df}^{m1} + V_{do}^{m1}
$$

$$
L_g \frac{d{i}_{qf}^{m1}}{dt} = -L_g m_1 \omega i_{df}^{m1} - R_g i_{qf}^{m1} - V_{qf}^{m1} + V_{qo}^{m1}
$$

$$
L_g \frac{d{i}_{df}^{m2}}{dt} = -L_g m_2 \omega i_{qf}^{m2} - R_g i_{df}^{m2} - V_{df}^{m2} + V_{do}^{m2}
$$

$$
L_g \frac{d{i}_{qf}^{m2}}{dt} = L_g m_2 \omega i_{df}^{m2} - R_g i_{qf}^{m2} - V_{qf}^{m2} + V_{qo}^{m2}
$$

(4.13)

The time models for an $m_1$ and an $m_2$ are discretized based on (3.18). Hence state space model on a per component bases is defined as,

$$
X_{GF}^{+m1}(k+1) = A_{GF}^{+m1} X_{GF}^{+m1}(k) + B_{GF}^{+m1} U_{GF}^{+m1}(k) + H_{GF}^{+m1} W_{GF}^{+m1}(k)
$$

(4.14)

For a negative sequence voltage component,

$$
X_{GF}^{-m2}(k+1) = A_{GF}^{-m2} X_{GF}^{-m2}(k) + B_{GF}^{-m2} U_{GF}^{-m2}(k) + H_{GF}^{-m2} W_{GF}^{-m2}(k)
$$

(4.15)

Definition of all state vector for sequence components are as follows,

$$
X_{GF}^{+m1}(k) = \begin{bmatrix}
V_{df}^{+m1} & V_{qf}^{+m1} & i_{df}^{+m1} & i_{qf}^{+m1}
\end{bmatrix}^T
$$

$$
W_{GF}^{+m1}(k) = \begin{bmatrix}
i_{df}^{+m1} & i_{qf}^{+m1}
\end{bmatrix}^T
$$

(4.16)
\[ X_{GF}^{-m_2}(k) = \begin{bmatrix} V_{df}^{-m_2} & V_{df}^{-m_2} & i_{df}^{-m_2} & i_{qf}^{-m_2} \end{bmatrix}^T \]

\[ W_{GF}^{-m_2}(k) = \begin{bmatrix} i_{df}^{-m_2} & i_{qf}^{-m_2} \end{bmatrix}^T \] (4.17)

Model matrices are also naturally defined in terms of the extracted components as,

\[
A_{GF}^{+m_1} = \begin{bmatrix} 1 & m_1 \omega T_s & T_s / C_g & 0 \\
-m_1 \omega T_s & 1 & 0 & T_s / C_g \\
T_s / L_g & 0 & (1 - R_g T_s / L_g) & m_1 \omega T_s \\
0 & T_s / L_g & -m_1 \omega T_s & (1 - R_g T_s / L_g) \end{bmatrix} \tag{4.18}
\]

\[
A_{GF}^{-m_2} = \begin{bmatrix} 1 & -m_2 \omega T_s & T_s / C_g & 0 \\
m_2 \omega T_s & 1 & 0 & T_s / C_g \\
T_s / L_g & 0 & (1 - R_g T_s / L_g) & -m_2 \omega T_s \\
0 & T_s / L_g & m_2 \omega T_s & (1 - R_g T_s / L_g) \end{bmatrix} \tag{4.19}
\]

Matrices \( B_{GF}^{+m_1}, H_{GF}^{+m_1}, B_{GF}^{-m_2} \) and \( H_{GF}^{-m_2} \) carry the same definition as in (3.25).

### 4.3.2 Proposed Multi-Component Voltage Control Based on a Local FCS-MPC for GF Converter

The objective of the controls for this converter is to:

1. Set up the positive sequence voltage through regulation of capacitor voltage to a reference higher than the nominal by the voltage drop at rated conditions.
2. Set all the fundamental/harmonic negative and harmonic positive sequence voltage components to zero.

For a distributed model predictive control, the interaction matrices are obtained by comparing models of (4.14) and (4.15) to (3.26) and are defined as,

\[ A_{ij}^{+m_1} = [0], A_{ij}^{-m_2} = [0], B_{ij}^{+m_1} = [0] \text{ and } B_{ij}^{-m_2} = [0] \] (4.19)

The control method in [76] with the modifications implemented in Chapter 3.0 is further extended in the present work. Since the converter supplies fundamental and
harmonic positive and negative sequence currents (due to linear and non-linear loading conditions), the method is further modified to account for all of these components. The controls of a GF converter can be summarized as follows.

1. State vectors $X_{GF}^{+m1}$ and $X_{GF}^{-m2}$ are predicted to obtain one step ahead predictions using (4.14) and (4.15), based on decomposition and extraction related to measurements made at instant $k$.

2. Predicted filter current is evaluated for all possible switching pattern [76], this includes all positive and negative extracted current components for fundamental or harmonic order. The input to the state space model, used in the prediction of currents, is equal to the output voltage of the converter [117]. For the proposed method, we need to define an input for every extracted component model from the three phase measurements of GF filter current. Hence, the inputs for model (4.14) and (4.15) are defined as,

$$U_{GF}^{+m1}(k) = \frac{2}{3} V_{dc} \begin{bmatrix} \cos(m_1 \theta) & \sin(m_1 \theta) \end{bmatrix} \begin{bmatrix} 1 & -0.5 & -0.5 \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} SW$$ (4.20)

And

$$U_{GF}^{-m2}(k) = \frac{2}{3} V_{dc} \begin{bmatrix} \cos(-m_2 \theta) & \sin(-m_2 \theta) \end{bmatrix} \begin{bmatrix} 1 & -0.5 & -0.5 \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} SW$$ (4.21)

for positive and negative sequence currents components respectively.

3. Second step voltage prediction is implemented based on $k + 1$ predicted voltage and filter current [76] found in step 1 for all $m_1$ and $m_2$ voltage components.

4. A cost function, which utilizes the second step voltage predictions is evaluated for every switching pattern [76] per fundamental and harmonic components in both
sequences. The pattern that achieves a minimum value is selected and directly applied to the converter at the next sampling instant. The cost function for positive sequence voltage components is defined by,

\[
J^+_{GF} = (V^+_{dq\text{ref}} - V^+_{dqf}(k + 2))^T (V^+_{dq\text{ref}} - V^+_{dqf}(k + 2)) + (V^+_{dq\text{ref}} - V^+_{dqf}(k + 2))^T (V^+_{dq\text{ref}} - V^+_{dqf}(k + 2)) \tag{4.22}
\]

And for negative sequence,

\[
J^-_{GF} = (V^-_{dq\text{ref}} - V^-_{dqf}(k + 2))^T (V^-_{dq\text{ref}} - V^-_{dqf}(k + 2)) + (V^-_{dq\text{ref}} - V^-_{dqf}(k + 2))^T (V^-_{dq\text{ref}} - V^-_{dqf}(k + 2)) \tag{4.23}
\]

Finally, the composite cost function of the subsystem controller that is minimized is,

\[
J_{GF} = J^+_{GF} + J^-_{GF} \tag{4.24}
\]

The vectors, \(V_{dq\text{ref}}\) and \(V_{dq}(k + 2)\) are the reference and second step predictions of associated sequence voltage components. A block diagram of the proposed distributed per component voltage control strategy of GF converter is shown in Fig. 4.4.
Figure 4.4 Proposed Control Block Diagram of GF Converter Based on Distributed FCS-MPC with Multi-SRF Decomposition and Extraction
4.4 Multiple Component Based Control for a Grid Following Subsystem

These converters are controlled to supply \( m_1 \) and \( m_2 \) current components according to share factors. The share factors, which in this work are issued per component per sequence, are determined by a control center that manages the microgrid operations.

4.4.1 Component Based Mathematical Modeling of Grid Following Converter

The current delivered by each GFE converter is rotated at frames that have different angles. As depicted by (4.6), stationary reference frame current is rotated at \( \omega t, -\omega t, -5\omega t \) and \( 7\omega t \) respectively. Each extracted current component can be mathematically modeled. The state space vector expression of voltage balance at the terminals of the converter is given by,

\[
(L_f + L_i) \frac{di}{dt} = -(R_f + R_i)i - Vp + \bar{V}
\]  

(4.25)

where \( V \) is the output terminal voltage of the converter. Based on the multiple SRF extracted components and in terms of \( m_1 \) and \( m_2 \) components, the voltage balance is expressed as,

\[
(L_f + L_i) \frac{d(i_{dq}^{m1} e^{j\omega t})}{dt} = -(R_f + R_i)i_{dq}^{m1} e^{j\omega t} - V_{dq}^{m1} e^{j\omega t} + V_{dq}^{m1} e^{j\omega t}
\]  

(4.26)

\[
(L_f + L_i) \frac{d(i_{dq}^{m2} e^{-j\omega t})}{dt} = -(R_f + R_i)i_{dq}^{m2} e^{-j\omega t} - V_{dq}^{m2} e^{-j\omega t} + V_{dq}^{m2} e^{-j\omega t}
\]  

(4.27)

where \( V_{dq} \) is the output voltage of GFE converter in \( dq \) axes at the related frame. On a per axis bases each \( m_1 \) or \( m_2 \) current component can be expressed as,
\[
(L_f + L_i) \frac{d^{+m_1}}{dt} = (L_f + L_i)m_1 \omega i_{d}^{+m_1} - (R_f + R_i)i_{d}^{+m_1} - Vp_{d}^{+m_1} + V_{d}^{+m_1} \\
(4.28)
\]

\[
(L_f + L_i) \frac{d^{+m_1}}{dt} = -(L_f + L_i)m_1 \omega i_{d}^{+m_1} - (R_f + R_i)i_{q}^{+m_1} - Vp_{q}^{+m_1} + V_{q}^{+m_1} \\
(4.29)
\]

To provide discrete predictions, a similar procedure is followed to that of GF converter. Hence a delivered positive sequence current component by a GFE converter is modelled in state space as,

\[
X^{+m_1}(k + 1) = A^{+m_1}X^{+m_1}(k) + B^{+m_1}U^{+m_1}(k) + H^{+m_1}W^{+m_1}(k) \\
(4.30)
\]

And for negative sequence delivered component,

\[
X^{-m_2}(k + 1) = A^{-m_2}X^{-m_2}(k) + B^{-m_2}U^{-m_2}(k) + H^{-m_2}W^{-m_2}(k) \\
(4.31)
\]

The state vectors for the GFE converter are,

\[
X^{+m_1}(k) = \begin{bmatrix} i_d^{+m_1}(k) & i_q^{+m_1}(k) \end{bmatrix}^T \\
(4.32)
\]

\[
X^{-m_2}(k) = \begin{bmatrix} i_d^{-m_2}(k) & i_q^{-m_2}(k) \end{bmatrix}^T \\
(4.33)
\]

\[
W^{+m_1}(k) = \begin{bmatrix} Vp_d^{+m_1}(k) & Vp_q^{+m_1}(k) \end{bmatrix}^T \\
(4.34)
\]

\[
W^{-m_2}(k) = \begin{bmatrix} Vp_d^{-m_2}(k) & Vp_q^{-m_2}(k) \end{bmatrix}^T \\
(4.35)
\]

The matrices of the per component model are,
\[ A^{+m_1} = \begin{pmatrix} 1 - \frac{R_f + R_l T_s}{L_f + L_l T_s} & m_1 \omega T_s \\ -m_1 \omega T_s & 1 - \frac{R_f + R_l T_s}{L_f + L_l T_s} \end{pmatrix} \]

\[ A^{-m_2} = \begin{pmatrix} 1 - \frac{R_f + R_l T_s}{L_f + L_l T_s} & -m_2 \omega T_s \\ m_2 \omega T_s & 1 - \frac{R_f + R_l T_s}{L_f + L_l T_s} \end{pmatrix} \] (4.36)

The B and H matrices are the same as these determined by (3.43).

### 4.4.2 Proposed Multi-Component Current Control Based on a Local FCS-MPC for a GFE Converter

In the section, the proposed current control strategy is presented. Controls are implemented using a FCS-MPC that is associated with each subsystem converter operated as a GFE. The local objective, whether in grid or island mode is to achieve a component based current regulation. Generally, current control using FCS-MPC has a target of minimizing differences between model generated predictions and reference settings [71].

In the work presented here, this covers all considered current components in the control process. Since each subsystem has its associated controller, coupling matrices, for the first GFE subsystem, \( i = 1 \) relative to the \( j^{th} \) GFE operated subsystem in the microgrid is defined in terms of the extracted current components \( m_1 \) and \( m_2 \) are,

\[ A_{1j}^{+m_1} = H^{+m_1}, A_{1j}^{-m_2} = H^{-m_2}, B_{1j}^{+m_1} = B_{1j}^{-m_2} = [0] \] (4.37)

Current control procedure for a GFE subsystem can be achieved by the following steps:

1. Current components, \( m_1 \) and \( m_2 \), are predicted for instant \( k + 1 \) by using models (4.30) and (4.31) based on components extracted from measured converter current and PCC voltage.
2. The reference settings are obtained from the share factors which are, $SF_i^{m1}$ and $SF_i^{-m2}$ for the $i^{th}$ GFE converter and load current at the PCC. Hence if the extracted load current components are, $i_{dqL}^{m1}$ and $i_{dqL}^{-m2}$, the reference vector is defined as,

$$i_{dqref}^{m1} = SF_i^{m1}[i_{dl}^{m1}(k) \ i_{ql}^{m1}(k)]^T \quad (4.38)$$

$$i_{dqref}^{-m2} = SF_i^{-m2}[i_{dl}^{-m2}(k) \ i_{ql}^{-m2}(k)]^T \quad (4.39)$$

3. The cost function for the considered positive sequence components is defined as,

$$J_{GFE}^+ = \left(i_{dqref}^+ - i_{dq}^+(k + 1)\right)^T \left(i_{dqref}^+ - i_{dq}^+(k + 1)\right) + \left(i_{dqref}^7 - i_{dq}^7(k + 1)\right)^T \left(i_{dqref}^7 - i_{dq}^7(k + 1)\right) \quad (4.40)$$

And for negative sequence components,

$$J_{GFE}^- = \left(i_{dqref}^- - i_{dq}^-(k + 1)\right)^T \left(i_{dqref}^- - i_{dq}^-(k + 1)\right) + \left(i_{dqref}^- - i_{dq}^-(k + 1)\right)^T \left(i_{dqref}^- - i_{dq}^-(k + 1)\right) \quad (4.41)$$

The switching pattern $a^k + 1$ is determined from the composite function defined as,

$$J_{GFE} = J_{GFE}^+ + J_{GFE}^- \quad (4.42)$$

Here local controller of a GFE subsystem regulates each sequence component towards the reference setting. Hence the current delivered to the PCC loads, based on the
defined share factors, serves the global objective of maintaining power/demand balance. Details of the proposed multi components FCS-MPC based is shown in Fig. 4.5.

Figure 4.5 Proposed Control Block Diagram of GFE Converter Based on Distributed FCS-MPC with Multi-SRF Decomposition and Extraction
4.5 Multi-Component Decomposition and Extraction of Load Current

As stated in the control process of GFE converters, a reference for each sequence component is needed so as to facilitate the regulation process. The current measured at PCC is rotated at multiple frames. This is followed by a filtering process to obtain the corresponding current components. Figure 4.6 shows a block diagram of component extraction of load current.

4.6 Simulation and Results

In this section, a validation of the voltage and current control strategies proposed in the sections above is simulated. Two modes of operation for the microgrid is
investigated. The first is a non-stiff network and then an island mode of operation is considered. In grid mode, the grid impedance is considered equal to \( Z_g = 1.2 + j0.377 \Omega \) which represents a low short circuit KVA level.

4.6.1 Performance of per Component Voltage Strategy for GF Converter Subsystem

In this part, validation of the control approach for GF converter is considered. The converter, for this part of the simulation, supplies all of the load current (GFEs are not switched) that include fundamentals for both sequences, 5\(^{th}\) and 7\(^{th}\) harmonics components. The voltage across the Capacitor is decomposed using multi-SRF and all voltage components are predicted according to the state space model \`associated with a GF converter. As for reference setting, all predicted voltage components are regulated to zero except for the positive sequence fundamental component. The latter component is controlled to follow a reference equal to the nominal PCC voltage plus voltage drop at conditions where all loads are switched on. Figure 4.7, shows tracking response of per component distributed FCS-MPC approach for capacitor voltage in \( abc \) stationary frame. It can be concluded that the voltage measured across the capacitor of the GF converter follow its positive sequence reference setting with very little error even with the non-fundamental voltage components are present in the converter circuit. This is due the action of the cost functions for local controller as defined by (4.22), (4.23) and (4.24), which encompasses all sequence voltage components.

Several practical situation may call for a sudden change to reference settings. Hence it is essential that the proposed controller is validated against an increase/decrease in target voltage. For that purpose, a step increase in the reference setting is initiated at, \( t = 0.7 \, sec \),
and a decrease at, $t = 0.8 \text{ sec}$. Results verify that the controller is still able to track the reference voltage setting with a well-tolerated error. A fast control action is observed for the step change which increases the reference by 20%, where the actual capacitor voltage rapidly tracks the new reference settings. The reference change profile and corresponding controller response are shown in Fig. 4.8. The same is true for a decrease in reference settings. Therefore, the proposed voltage controller proves itself to be robust to any sudden alteration in the reference value providing adequate tracking in about one cycle of the fundamental frequency.

Figure 4.7 Voltage Tracking Based on the Proposed per Component FCS-MPC of a GF Subsystem Converter
Figure 4.8 Voltage Reference for Distributed FCS-MPC of GF Controller, (a) Step Change and (b) Tracking Performance
4.6.2 Performance for Grid Mode of Operation

In this section of the simulation, the nonlinear load is switched at \( t = 0.3 \text{ sec} \), while balanced and unbalanced loads are switched at \( t = 0.1 \text{ and } 0.2 \text{ sec} \) respectively. All GFE subsystems are switched at \( t = 0.5 \text{ sec} \). In this case a non-stiff utility grid is considered. Figure 4.9 shows the tracking performance for positive rotating components (1\textsuperscript{st} and 7\textsuperscript{th}) in dq axes. The positive sequence current, \( i_{dq}^{+1} \) represents the fundamental current due to the linear and non-linear load. Regulation of negative sequence components (1\textsuperscript{st} and 5\textsuperscript{th}) are shown in Fig. 4.9 (b) for GFE1. Satisfactory regulation is obtained. However, there are some offsets at instances and this can be related to the different magnitudes of components in the cost function. Reference settings, per component, for GFE1 are determined based on share factors defined as, \( SF_1^{+1} = 50\% \text{ and } SF_1^{+7} = 30\% \) for positive sequence components and negative sequence current components shares are, \( SF_1^{-1} = 50\% \text{ and } SF_1^{-5} = 40\% \). The second current feeding unit, GFE2, has share factors for sequence components as, \( SF_2^{+1} = 30\% , SF_2^{+7} = 40\% , SF_2^{-1} = 30\% \text{ and } SF_2^{-5} = 40\% \). Tracking for various current components are shown in Fig. 4.10 for GFE2. Voltage and current at the PCC are shown in Fig.4.11 (a)-(b) respectively. Here results confirm that the total current drawn from grid undergoes a high decrease. This is due to the microgrid subsystems GFE1 and GFE2. These two units supply jointly about 80\% of the total load current measured at the PCC. This also validates that grid current is more balanced since in this case only 20\% of the negative sequence current is supplied by the grid. This verifies the effectiveness of the proposed approach in providing additional services by microgrid units to the utility grid, not only participating in supplying a share of the load, but also achieving a more balanced grid current by individually sharing the negative sequence
current. Here, each GFE subsystem optimizes its performance to participate in the overall global objective of maintaining a balance between available and demanded power.

The PCC voltage of Fig. 4.11(b) which is shown for pre/post switching of GFE subsystems and 0.15 sec. after switching reveals two observations:

1. Prior to switching of GFEs, that is $0.45 \leq t \leq 0.5$ sec., the PCC voltage undergoes a considerable drop since the grid impedance is high (low short circuit KVA is assumed) and delivers all load current. However, post switching of GFEs, the voltage profile is boosted due to the considerably reduced sum of voltage drops associated with the current components of PCC load current. Positive sequence voltage profile is shown in Fig. 4.12 (a), which conforms the boost in voltage at PCC.

2. The PCC voltage has a high amount of harmonic content after switching of GFEs. This is due to the effect of the weak grid which cannot obstruct harmonics from GFE1 and GFE2 [118].

3. An additional observation from the PCC voltage is that it shows a more balanced behavior after $t = 0.5$ sec. due to the reduction of negative sequence drop defined by, $i_{dqgrd}Z_g$. The amount of negative sequence content in the PCC is shown in Fig. 4.12 (b). The UVF corresponding to the negative sequence share factors for GFE1 and GFE2 mention above is calculated as $UVF = 2.571\%$. 
Figure 4.9 Tracking Performance of Local FCS-MPC at Switching of GFE1 and 0.15 sec. After, (a) Positive and (b) Negative Sequence Components
Figure 4.10 Tracking Performance of Local FCS-MPC at Switching of GFE2 and 0.15 sec. After, (a) Positive and (b) Negative Sequence Components
Figure 4.11 Pre/Post and 0.15 sec. After GFEs Switching PCC Measured (a) Current and (b) Voltage.

Figure 4.12 Sequence Voltage Content of Microgrid PCC Voltage under Weak Utility Grid Condition. (a) Positive and (b) Negative.
4.6.3 Performance for Island Mode of Operation

In this part an islanded microgrid is considered in the validation of the proposed distributed FCS-MPC with multi-SRF decomposition and extraction. In this case a GF subsystem is used to act in place of the disconnected utility grid. The voltage control strategy implemented in per component has already been validated in Section 4.5.1. Therefore, the purpose of this part is to investigate current tracking with the two GFEs operating with a GF unit. For this case, each GFE unit supplies 30% and 40% of fundamental sequences and harmonic component respectively. All GFEs are switched at \( t = 0.5 \text{ sec} \). Tracking response associated with GFE1 local controller is shown in Fig. 4.13 for both sequences. Controller of GFE2 achieves tracking behavior as depicted in Fig. 4.14. Results show that components follow their reference settings. However, some oscillations are observed in the fundamental negative sequence for the island mode. This is related to the small reference values of some current components. Voltage and current at PCC for this island mode of operation is shown in Fig. 4.15. Here the GF converter supplies 40% of fundamental sequence components and 20% of harmonic components. Hence as shown in Fig. 4.15 (a), the GF current tends to be balanced. The PCC voltage in Fig. 4.15 (b) has high distortion due to injection of harmonics by all converters. In Fig. 4.15 (a), the load current supplied by the GF converter, \( i_{abcg} \), has a high value compared to that supplied in the grid mode operation (Fig. 4.11 (a)), prior to switching of GFEs. This is due to the high reference value set out for the capacitor voltage of the GF subsystem which compensates for the voltage drop at full load conditions and achieves a high PCC voltage profile. This is evident from Fig. 4.15 (b) for the period \( t \leq 0.5 \text{ sec} \).
Figure 4.13 Tracking Performance of Local FCS-MPC for Island Mode at Switching of GFE1 and 0.15 sec. After, (a) Positive and (b) Negative Sequence Components
Figure 4.14 Tracking Performance of Local FCS-MPC for Island Mode at Switching of GFE2 and 0.15 sec. After, (a) Positive and (b) Negative Sequence Components
4.6.4 Verification of Decoupled Input for DMPC of Microgrid Subsystems

In this part an investigation of the decoupled input is carried out for the new loading conditions. A grid mode operation is assumed, with share factors that corresponds to 30% of fundamental positive and negative sequence current components are supplied by GFE1 and GFE2. Harmonics components are shared according to share factors defined as, $SF^{-5}_1 = 0$ and $SF^{+7}_1 = 0$ for GFE1, and $SF^{-5}_2 = 40\%$, $SF^{+7}_2 = 40\%$ for GFE2. In second case, share factors of GFE1 are changed to $SF^{+1}_1 = 50\%$, $SF^{-1}_1 = 50\%$, $SF^{-5}_1 = 30\%$ and $SF^{+7}_1 = 30\%$, whereas GFE2 share factors remain the same. Based on (3.53) and (3.54), data for $C_{avg}$ are summarized in Table 4.2 below.
Table 4.2 Average and Percentage Change in Number of Commutations for GFE Converters With Linear and Non-linear Loading

<table>
<thead>
<tr>
<th>Case #</th>
<th>$C_{avg \ GFE1}$</th>
<th>$C_{avg \ GFE2}$</th>
<th>$% C_{avg \ GFE1}$</th>
<th>$% C_{avg \ GFE2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2412</td>
<td>2547</td>
<td>3.648 %</td>
<td>2.866 %</td>
</tr>
<tr>
<td>2</td>
<td>2324</td>
<td>2474</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Two main points can be deduced from the data of Table 4.2. The first is that despite the addition of positive and negative sequence harmonic components shares for the controller of GFE1, the average number of switch commutations decreases. Hence shares can be altered in reference vectors without increase in the average commutation of a switch for the converter of the microgrid subsystem. The second point is related to the decoupling of inputs as share factors one system undergoes a change. The average commutation undergoes a change of only 2.866 % for GFE2 subsystem despite the major change in share factors of GFE1. Therefore, a very insignificant and a safely negligible effect is observed in the considered microgrid topology. Tracking efficiency of GFE1 controller for case 1 and 2 are shown in Fig. 4.16.
Figure 4.16 FCS-MPC Tracking Behavior, (a) Positive, (b) Negative Sequence for Case 1, (c) Positive and (b) Negative Sequence for Case 2
4.7 Summary

In this chapter the decomposition and extraction of voltages and currents relevant to the control system is implemented based on a multi-SRF approach. The loads at the PCC of the microgrid and utility grid are composed from four linear loads with one non-linear load. To further increase unbalanced loading conditions, two phase loads have also been embedded in the PCC. Voltage and current control strategies based on the distributed FCS-MPC have been proposed and validated under grid and island modes of operation. Also, interactions between GFE subsystems characterized by the number of switching commutation of a subsystem relative to a change in tracking pattern of another is investigated.
5.1 Introduction

In many practical situations a utility grid experiences non-sinusoidal voltage conditions. These non-ideal cases may include unbalance and distorted supply. Two objectives are sought in this chapter. The first is to compare extracted components obtained from the multi-SRF presented in Chapter 4.0 with those obtained from a power theory. Here, the multi-SRF performance in obtaining components under non-ideal utility grid compared to the Current Physical Component Theory (CPCT) is examined. This theory, which is reported as a well suited concept for explaining power phenomena in non-ideal supply [123]. For the purpose of comparison with the multi-SRF, current components obtained by the aforementioned theory have to be transformed to SRF at different frequency orders. The second objective is to validate the proposed per component FCS-MPC under a distorted grid mode of operation.

5.2 Extraction of Current Components under Asymmetrical and Distorted Utility Grid Voltage by Synchronous Reference Frames

In this chapter, grid mode of operation is investigated under different conditions of utility supply. The system under consideration is the same as that of Fig. 4.1 but with the following modifications:

1. No GF converters are present.
2. The utility grid is assumed to be contaminated with a negative sequence voltage component of magnitude defined as a fraction of nominal positive sequence voltage, that is, \( V^{-1}/V^1 \).

3. The utility grid has harmonic voltage components of negative and positive sequences. The work in this chapter will also consider 5\(^{th}\) and 7\(^{th}\) components with normalized magnitudes defined as \( V^{-5}/V^1 \) and \( V^7/V^1 \) respectively.

4. One unbalanced three phase load is present at the PCC.

The system under consideration is shown in Fig. 5.1 with the above mentioned modifications.

Figure 5.1 Per Phase Schematic of a Microgrid under Linear and Non-linear Loading Conditions with a k GFE Subsystems
Current components which are expressed as fundamental and harmonic, in positive and negative sequences, originate from the voltage supply asymmetry/distortion on one hand and from unbalanced and non-linear loads on the other. According to the superposition principle the total effect is obtained from individual contributions. Utility grid voltage in $\alpha\beta$ stationary frame is written as,

$$V_{\alpha\beta} = V_{dq}^+ e^{j\omega t} + V_{dq}^- e^{-j\omega t} + V_{dq}^5 e^{-j5\omega t} + V_{dq}^7 e^{+j7\omega t}$$ \hspace{1cm} (5.1)$$

where $V_{dq}$ is the supply voltage in SRF per sequence component and $\omega$ is nominal angular frequency of system. Based on measurements at the PCC, the equivalent admittance defined for an $m^{th}$ current component is given by,

$$Y_{eqm} = Y_m e^{-j\theta_m}$$ \hspace{1cm} (5.2)$$

If (5.1) is expressed in terms of current components and admittances then,

$$V_{\alpha\beta} = \frac{i_{dq}^+}{Y_1} e^{j(\omega t + \theta_1)} + \frac{i_{dq}^-}{Y_1} e^{-j(\omega t - \theta_2)} + \frac{i_{dq}^5}{Y_5} e^{-j(5\omega t - \theta_5)} + \frac{i_{dq}^7}{Y_7} e^{j(7\omega t + \theta_7)}$$ \hspace{1cm} (5.3)$$

where $I_{dq}$ is the current defined in SRF per sequence component due to source asymmetry ($m = 1$) and non-ideality ($m = 5$ or $7$) effects. To extract fundamental positive sequence component of current due to grid voltage asymmetry/distortion, (5.3) is multiplied by $e^{-j\omega t}$,

$$\frac{i_{\alpha\beta}}{Y_1} e^{-j\omega t} = \frac{i_{dq}^+}{Y_1} e^{j(\theta_1)} + \frac{i_{dq}^-}{Y_1} e^{-j(2\omega t - \theta_2)} + \frac{i_{dq}^5}{Y_5} e^{-j(5\omega t - \theta_5)} + \frac{i_{dq}^7}{Y_7} e^{j(6\omega t + \theta_7)}$$ \hspace{1cm} (5.4)$$
Simplifying (5.4), results in (5.5) which again shows that the fundamental current component required is embedded with multi AC components, this equation is,

\[ i_{\alpha\beta}e^{-j\omega t} = i_{dq}^{+}e^{j(2\omega t+\phi_1)} + i_{dq}^{-}e^{j(4\omega t+\phi_3)} + \frac{Y_1}{Y_5}i_{dq}^{-5}e^{-j(6\omega t-\phi_3)} + \frac{Y_1}{Y_7}i_{dq}^{7}e^{j(6\omega t+\phi_7)} \]  

(5.5)

In (5.4) and (5.5), the magnitude of admittances the load presents to positive and negative sequence are assumed to be equivalent. These components are filtered out using the multi notch filter used in the previous chapter. Following similar procedure negative fundamental, negative 5th and positive 7th source affiliated current components can be written as in (5.6),

\[ i_{\alpha\beta}e^{j\omega t} = i_{dq}^{+1}e^{j(2\omega t+\phi_1)} + i_{dq}^{-1}e^{j(4\omega t-\phi_3)} + \frac{Y_1}{Y_5}i_{dq}^{-5}e^{j(4\omega t-\phi_3)} + \frac{Y_1}{Y_7}i_{dq}^{7}e^{j(6\omega t+\phi_7)} \]  

(5.6)

\[ i_{\alpha\beta}e^{-j\omega t} = \frac{Y_2}{Y_1}i_{dq}^{+1}e^{-j(6\omega t+\phi_1)} + \frac{Y_5}{Y_1}i_{dq}^{-1}e^{j(4\omega t+\phi_3)} + \frac{Y_5}{Y_7}i_{dq}^{-5}e^{j(8\omega t+\phi_3)} + \frac{Y_5}{Y_7}i_{dq}^{7}e^{j(12\omega t+\phi_7)} \]  

(5.6)

Contribution of the load unbalance and non-linearity is now considered, where a clean supply is assumed. In this case the decomposition is as expressed by (4.4) of the previous chapter. To get the total effect, (4.4) is combined with decomposed current components defined by (5.5) and (5.6). This defines current components due to both grid voltage asymmetry/ or distortion with these obtained by unbalanced and non-linear loads encountered at the PCC. Hence overall components of the system for each considered order are,
where $i_{\alpha\beta T}$ is the PCC current due to source and loading effects. These components according to the presented SRF approach yields desired component by one transformation only of the load current at microgrid PCC.

### 5.3 Current Physical Component Theory Based Decomposition

The CPCT facilitates current decomposition that are related to power phenomena in electrical grids. According to this theory, current components are obtained based on complex root mean square of voltage and equivalent load admittances. Generally, for a combination of balanced, unbalanced and non-linear loading effects, three components of current are obtained which are balanced, unbalanced and reactive component [99]. These components are obtained as complex RMS, which for the purpose of comparison in this work need to be converted to time domain. The equivalent load admittance can be determined with one phase as reference hence only two admittances need to be calculated.
[103]. If phase A is reference, the load admittance per $m$ voltage and current components are defined as,

$$ Y_{Ca,m} = \frac{I^m_C}{V_{CA}^m}, Y_{Ba,m} = \frac{I^m_B}{V_{BA}^m} $$  \hspace{1cm} (5.11)

Here current and voltage are CRMS which are determined by the recursive discrete Fourier transform (RDFT) [102, 124]. The admittance which corresponds to the unbalancing effect across the phases at a balanced supply (load unbalance only) is defined based on three admittances in [99, 125]. Based on two admittances with phase A as reference, it is defined,

$$ Y_{Um} = -(\alpha^m Y_{Ca,m} + \alpha^{2m} Y_{Ba,m}) $$  \hspace{1cm} (5.12)

With $\alpha^m = e^{jm2\pi/3}$. Hence CRMS of active, reactive and unbalanced components at fundamental and harmonic frequencies are [125],

$$ I^m_R = Re(Y_{Ca,m} + Y_{Ba,m})V^m $$  \hspace{1cm} (5.13)

$$ I^m_R = Img(Y_{Ca,m} + Y_{Ba,m})V^m $$  \hspace{1cm} (5.14)

$$ I^m_U = |Y_{Um}|V^m $$  \hspace{1cm} (5.15)

Here $V^m$ is the RMS voltage per phase of the PCC voltage $Vp$ for an $m$ order component. To get time domain components, active and reactive components rotate in
positive or negative direction, whereas the unbalanced rotates in negative direction. Therefore, these expressions are,

\[ i_{A}^{m} = \sqrt{2} l_{A}^{m} \sin(m \omega t) \]
\[ i_{BA}^{m} = \sqrt{2} l_{BA}^{m} \sin(m \omega t - h \pi / 3) \]
\[ i_{CA}^{m} = \sqrt{2} l_{CA}^{m} \sin(m \omega t - q \pi / 3) \]

\[ i_{AR}^{m} = \sqrt{2} l_{AR}^{m} \sin(m \omega t + \pi / 2) \]
\[ i_{BR}^{m} = \sqrt{2} l_{BR}^{m} \sin(m \omega t - h \pi / 3 + \pi / 2) \]
\[ i_{CR}^{m} = \sqrt{2} l_{CR}^{m} \sin(m \omega t - q \pi / 3 + \pi / 2) \]

\[ i_{AU}^{m} = \sqrt{2} l_{AU}^{m} \sin(m \omega t + \phi_{m}) \]
\[ i_{BU}^{m} = \sqrt{2} l_{BU}^{m} \sin(m \omega t - h \pi / 3 + \phi_{m}) \]
\[ i_{CU}^{m} = \sqrt{2} l_{CU}^{m} \sin(m \omega t - q \pi / 3 + \phi_{m}) \]

where \( \phi_{m} \) is the angle of \( Y_{um} \).

In the above time domain expressions, (5.18) is of negative sequence rotation. This will reflect the negative sequence current due to unbalanced loading. As for (5.16) and (5.17) these are evaluated according to the Table 5.1. These expressions are used for the case of a distorted utility grid supply and non-linear loading, where, \( V^5, V^7 \neq 0 \) in (5.13) and (5.14). For the case of a distortion free supply \( (V^5, V^7 = 0) \) but with a non-linear load at the PCC, (5.13) and (5.14) cannot be used. Hence, the time domain harmonic per phase current is the difference between total measured current and the sum of active reactive and unbalanced calculated currents [101].
In the case of an asymmetrical supply voltage, and equivalent admittance, $Y_d$ is added to account for both load unbalancing and supply effect and is defined as [125],

$$Y_d = Y_e - \frac{3}{||U||^2} (Y_{BC}V_A^2 + Y_{CA}V_B^2 + Y_{AB}V_C^2)$$  \hspace{1cm} (5.19)

with $Y_e = Y_{BC} + Y_{CA} + Y_{AB}$ and $||U||^2 = V_A^2 + V_B^2 + V_C^2$

where $V_A, V_B$ and $V_C$ are the RMS of PCC voltage at fundamental frequency. Admittance $Y_d$ has a value if and only if two mutual events occurs, that is an unbalanced load and asymmetry voltage supply [125]. The load unbalance admittance due the asymmetrical utility supply (contaminated by a negative sequence component) [125] for two phases is,

$$Y_{U1}^{-1} = -(\alpha^2 Y_{CA} + a Y_{BA})$$  \hspace{1cm} (5.20)

Therefore, unbalanced current has two components, one due the positive whereas the other is due to negative sequence components of the supply voltage which is defined at the fundamental frequency as [125],

$$I_U^{+1} = Y_{U1}^{-1} V^{-1} - Y_d V^{+1}$$  \hspace{1cm} (5.21)

$$I_U^{-1} = Y_{U1}^{+1} V^{+1} - Y_d V^{-1}$$  \hspace{1cm} (5.22)
where $V^{+1}$ and $V^{-1}$ are the symmetrical components of the unbalanced supply obtained by Fortescue's transform matrix [126] and $Y^{+1}_{u\bar{1}}$ is determined by (5.12) with $m = 1$. Finally, the time domain active, reactive and unbalanced phase currents components for an unbalanced utility grid with a balanced, unbalanced and non-linear loads at the PCC for fundamental frequency is given by,

$$i_{aA}^1 = \sqrt{2}(l_a^{+1} + \text{Re}(l_u^{+1} + l_{\bar{u}}^{-1})) \sin(\omega t)$$

$$i_{bA}^1 = \sqrt{2}(l_b^{+1} + \text{Re}(l_u^{+1} + l_{\bar{u}}^{-1})) \sin(\omega t - 2\pi/3) \quad (5.23)$$

$$i_{cA}^1 = \sqrt{2}(l_c^{+1} + \text{Re}(l_u^{+1} + l_{\bar{u}}^{-1})) \sin(\omega t - 4\pi/3)$$

$$i_{aR}^1 = \sqrt{2}(l_r^{+1} + \text{img}(l_u^{+1} + l_{\bar{u}}^{-1})) \sin(\omega t + \pi/2)$$

$$i_{bR}^1 = \sqrt{2}(l_r^{+1} + \text{img}(l_u^{+1} + l_{\bar{u}}^{-1})) \sin(\omega t - 2\pi/3 + \pi/2) \quad (5.24)$$

$$i_{cR}^1 = \sqrt{2}(l_r^{+1} + \text{img}(l_u^{+1} + l_{\bar{u}}^{-1})) \sin(\omega t - 4\pi/3 + \pi/2)$$

$$i_{aU}^1 = \sqrt{2}(l_u^{+1} + l_{\bar{u}}^{-1}) \sin(\omega t)$$

$$i_{bU}^1 = \sqrt{2}(l_u^{+1} + l_{\bar{u}}^{-1}) \sin(\omega t - 4\pi/3) \quad (5.25)$$

$$i_{cU}^1 = \sqrt{2}(l_u^{+1} + l_{\bar{u}}^{-1}) \sin(\omega t - 2\pi/3)$$

The above components are calculated at fundamental frequency since the utility supply asymmetry adds negative sequence and therefore all harmonics related components are calculated by (5.16) and (5.17) as function of the considered harmonic order.

### 5.3.1 Current Physical Component Theory Implementation in SRF

To make a comparison in the same reference frame, components obtained from CPCT need to be transformed to SRF. For this purpose, the time domain expressions defined by (5.16),(5.17),(5.18),(5.23),(5.24) and (5.25) need to undergo an $abc/dq$
transform at frames that corresponds to those used in the proposed multi-SRF. The transform to synchrons frames of CPCT components is based on the assumptions that:

1. Unbalanced phase components, whether calculated by (5.18) or (5.25) are rotated at \( \omega t = -\theta \) only. Hence all unbalanced current component at the fundamental frequency from effect(s) of load, source or both are obtained from one of these two expressions depending on the condition considered.

2. Active current components are rotated at \( \omega t = \theta, \omega t = -5\theta \) and \( \omega t = 7\theta \) respectively. Hence, \( d \) axis of positive sequence fundamental and positive/negative harmonic components are obtained.

3. Reactive components in (5.17) are rotated at \( \omega t = \theta, \omega t = -5\theta \) and \( \omega t = 7\theta \) to obtain \( q \) axis component of fundamental positive and harmonic components.

Figure 5.2, shows a block diagram for the determination of CPCT components in SRF for the case of asymmetrical and distorted supply with a combined linear and non-linear loading. Here complex RMS voltage and current are obtained by the associated order of the current component considered. Extraction by CPCT for the case of supply grid voltage that is contaminated by negative sequence voltage component only but with linear and non-linear loading is shown in Fig. 5.3. In this case harmonic components 5\(^{th}\) and 7\(^{th}\) are calculated as the difference between total PCC current and sum of active, reactive and unbalanced components.

5.4 Simulation and Results

In this part three validation targets are pursued. The first is to compare current components extracted by multi-SRF of the microgrid system under study with counterparts
obtained through the CPCT for a symmetrical and non-distortive supply voltage. Second validation concerns evaluation of multi-SRF decomposition ability under asymmetrical and distorted grid voltage relative to the CPCT decomposition under the same supply conditions. Finally, the distributed FCS-MPC effectiveness in providing regulation of current components extracted by the multi-SRF with a distorted grid mode of operation with linear and non-linear loading is examined.

Figure 5.2 Load Current Decomposition by CPCT for a Utility Grid with Asymmetries and Distortion for Linear and Non-linear Loading

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5.4.1 Validation with Linear and Non-linear PCC Loads under Ideal Supply

In first case the unbalanced load is switched at \( t = 0.1 \text{ sec} \). According to the proposed SRF two frames are initiated which rotate at \( \omega t = \theta \) and \( -\theta \). These dq currents are compared with active, reactive and unbalanced current components of CPCT which are denoted as A1, R1 and U1 respectively. For example, A1 refers to the active component of the CPCT rotated at \( \omega t = \theta \) or \( -\theta \). Figure 5.4 depicts the current components corresponding to positive and negative sequence for this case. Here H components of the CPCT are harmonics current that are found as the difference between total PCC load current and sum of CPCT components as mentioned previously. Results verify that the proposed SRF yield equivalent components to those obtained by CPCT. It is worth mentioning that oscillations are observed at instant of unbalanced load switching in the proposed SRF method. This is due to the coupled positive current component \( i_{dq}^+ \) which ripples at 754 rad/sec for this considered case. As expected, since the source is ideal and
non-linear load is not switched, 5th and 7th order current components attain zero value when
the ripple components, $i_{dqL}^{+1}$ and $i_{dqL}^{-1}$ (rotating at 1508 rad/sec and 2262 rad/sec for a $5\omega t$
frame), die out.

At $t = 0.6$ sec., non-linear load is switched, decomposition and extraction are
shown in Figs. 5.5 (a)-(b). Results show that the proposed SRF produce components that
are exactly the same as the CPCT. Here both the SRF, $i_{dqL}^{+1}$ and CPCT active components
increase due to the fundamental positive sequence current of the non-linear load.
Figure 5.4 SRF and CPCT Performance under Ideal Supply, (a) Positive and (b) Negative Sequence Current Components
Figure 5.5 SRF and CPCT Performance under Ideal Supply, (a) Positive and (b) Negative Sequence Current Components
5.4.2 Validation for Asymmetrical Utility Supply with Balanced and Unbalanced Loads

In this case a utility voltage with a negative sequence voltage acts as the parent grid for the considered microgrid system. Hence, according to the mathematical model derived in Section 5.2, two negative sequence load current component exists. Figure 5.6 show results, where the unbalanced load has been switched for a long time. At $t = 0.6 \text{ sec}$, a negative sequence component, which is $30\%$ of the nominal positive sequence, is injected into the grid voltage. The SRF accurately detects the increase in the $i_{dq}^{-1}$ due to the supply asymmetry. The current, $i_{dq}^{+1} + i_{dql}^{+1}$, remains almost the same since positive sequence voltage is not effected. There is a very small difference in, $i_{dq}^{-1} + i_{dql}^{-1}$ between the U1 dq current of CPCT and SRF (-1). However, from a magnitude prospective, $|i_{dq}^{-1} + i_{dql}^{-1}|_{\text{SRF}(-1)} \approx |i_{dq}^{-1} + i_{dql}^{-1}|_{\text{CPCT(U1)}}$. Figure 5.7 considers the same conditions but with a 45% negative sequence component. The aim is to test the SRF performance for a high unbalance of utility grid supply. Results confirm the effectiveness of the SRF in reflecting sequence current component corresponding to this condition where the obtained components compare fairly strongly to those obtained from CPCT. Again Fig. 5.7 shows that there is a difference for negative sequence of SRF and CPCT but again the magnitudes are nearly equivalent. The negative sequence q axis current, $i_{q}^{-1} + i_{ql}^{-1}$ of CPCT is zero because the current phase angle is not considered as in (5.25). Results from this part of validation shows that components obtained from the multi-SRF and CPCT are strongly comparable in particular if the injected negative sequence has a small magnitude. At a ratio of 45% the two approaches have some differences but these fall within a well-tolerated range.
Figure 5.7 Current Components of SRF Compared to CPCT for $V^{-1}/V^+1=30\%$ with Linear Loading

Figure 5.6 Current Components of SRF Compared to CPCT for $V^{-1}/V^+1=45\%$ with Balanced and Unbalanced Loading
5.4.3 Validation for a Distorted Utility Supply with Linear and Non-linear Loads

In this part, a distorted utility supply is considered as a parent grid for the microgrid. Here all loads are connected. The distortion in the supply is assumed to be a 5\textsuperscript{th} and 7\textsuperscript{th} harmonic components of negative and positive sequence respectively. Figure 5.8 (a)-(b) show load current components of positive and negative sequences. Voltage harmonic components, injected at $t = 0.1 \text{ sec.}$, are 30\% and 20\% of the positive sequence nominal voltage for 5\textsuperscript{th} and 7\textsuperscript{th} orders respectively. The non-linear load is switched at $t = 0.4 \text{ sec.}$

To observe the effectiveness of the SRF decomposition method, the magnitude of the harmonic components for the 5\textsuperscript{th} and 7\textsuperscript{th} are changed to 40\% and 30\% respectively. Figure 5.9 depicts results for this condition. For SRF components, the fundamental current component of the non-linear load increases the $d$ axis component which corresponds to the PCC current rotated at $\omega t = \theta$. Naturally the 5\textsuperscript{th} and 7\textsuperscript{th} have added components which are $i_{dql}^{-5}$ and $i_{dql}^{+7}$ after, $t = 0.4 \text{ sec}$ as derived in (5.9) and (5.10) respectively. The negative sequence current as expected undergoes no change as the supply harmonics are injected. Hence negative sequence current at fundamental frequency reflects component related to the loading effect only. As it is evident from results the two approaches yield equivalent components. Even as the penetration of distorting components in utility grid supply is further increased, the multi-SRF is capable of producing sequence components that are equivalent to those obtained by the CPCT.
Figure 5.8 SRF and CPCT Performance for Linear and Non-linear Loading under Supply with $V^{+7}/V^{+1}$ =20%, $V^{-5}/V^{+1}$ =30% (a) Positive and (b) Negative Sequence Current Components
Figure 5.9 SRF and CPCT Performance for Linear and Non-linear Loading under Supply with $V^{+7}/V^{+1} = 30\%$, $V^{-5}/V^{-1} = 40\%$ (a) Positive and (b) Negative Sequence Current Components
5.4.4 Validation for Asymmetrical and Distorted Utility Supply with Linear and Non-linear Loads

In this part of the verification, the utility supply is assumed to contain negative sequence at one and five times the fundamental frequency with a $7\omega t$ positive sequence voltage component. In this case, the loading is the combined effect of linear and non-linear. Hence current components per sequence are from the accumulated effects of both supply non-ideality and loading effects. Negative fundamental, $5^{\text{th}}$ and $7^{\text{th}}$ harmonic components are $30\%$, $25\%$ and $20\%$ of the nominal positive sequence utility profile respectively. Extracted current components are shown in Fig. 5.10. For the case of higher asymmetry/distortion of supply, Fig. 5.11 depicts results for $1^{\text{st}}$ negative, $5^{\text{th}}$ negative and $7^{\text{th}}$ positive with ratios of $45\%$, $40\%$ and $30\%$ respectively. In all of results for this case the asymmetry and distortion components are injected at $t = 0.6 \text{ sec.}$, whereas the non-linear load is switched at $t = 0.8 \text{ sec.}$ The SRF current components compare very well with counterparts from CPCT. This is very well reflected especially for low asymmetry/distortion ratios. However, for high ratios there is a difference between SRF and CPCT. The percentage error is found to be $8.87\%$ for $i_{d}^{+1} + i_{dL}^{+1}$ and $13.82\%$ for $i_{q}^{+1} + i_{qL}^{+1}$ for SRF. It is worth mentioning that reference to Fig. 5.11, ratios of asymmetry and distortion adopted are quite high compared to practical situations. Hence for ratios that are comparable to practical situation the SRF components compare very well for a non-ideal utility grid and a combined balanced, unbalanced and non-linear loading conditions. One observation from harmonic current components obtained by the multi-SRF is that oscillations are encountered. This is prominent at conditions that corresponds to a utility grid with negative sequence voltage component. This may require additional filtering.
Figure 5.10 SRF and CPCT for Linear and Non-linear Loading with Supply Ratios of, $V^{-1}/V^{+1}=30\%$, $V^{-5}/V^{+1}=25\%$ and $V^{-7}/V^{+1}=20\%$, (a) Positive and (b) Negative Sequence Components
Figure 5.11 SRF and CPCT for Linear and Non-linear Loading with Supply Ratios of, $V^{-1}/V^{+1} = 45\%$, $V^{-5}/V^{+1} = 40\%$ and $V^{-7}/V^{+1} = 30\%$, (a) Positive and (b) Negative Sequence Components
5.4.5 Distributed FCS-MPC of Microgrid Units under Distorted Grid Supply with Linear and Non-linear Loading

Verification of the decomposition/ extraction method by multi- SRF proposed in Chapter 4.0 of this dissertation is implemented on a non-ideal supply of the utility grid which the microgrid system is hooked to. The purpose is to examine the FCS-MPC tracking performance. In this case a non-ideal supply contaminated with a 5th negative and 7th positive sequence component is considered. GFE 1 and 2 are switched at, \( t = 0.8 \text{ sec.} \), the share factors for each unit are 30% for fundamentals and harmonic sequence components. The harmonic voltage components ratios of the utility grid supply are 35% and 20% for 5th and 7th voltages respectively. Figure 5.12 shows tracking profile for GFE1. The FCS-MPC manages to produce adequate tracking in view of the non-linearity of grid voltage. This is attributed to well predicted current components model defined in (4.30) and (4.31) of Chapter 4.0. Here since a decomposition is implemented for the actual PCC voltage, the interacting states, which are the PCC dq voltage per \( m_1 \) and \( m_2 \) component, are incorporated in the model of the corresponding sequence current component. Tracking performance for GFE2 is depicted in Fig.5.13 and current supplied by grid is shown in Fig. 5.14. Naturally current exhibits an expected decrease since about 80% of load current are jointly delivered by microgrid GFE1 and GFE2 units. Results from Figs. 5.12 and 5.13 verify the applicability of the individual component control based on a local FCS-MPC for cases where the grid supporting the microgrid system suffers distortion conditions.
Figure 5.12 Tracking of FCS-MPC for GFE1 (a) Positive and (b) Negative Sequence Components with Supply Ratios, $V^{-1}/V^{+1} = 0\%$, $V^{5-}/V^{+1} = 35\%$ and $V^{7+}/V^{+1} = 20\%$ for Linear and Non-linear Loading
Figure 5.13 Tracking of FCS-MPC for GFE2 (a) Positive and (b) Negative Sequence Components with Supply Ratios, $V^{-1}/V^{++1} = 0\%$, $V^{-5}/V^{++1} = 35\%$ and $V^{++7}/V^{++1} = 20\%$ for Linear and Non-linear Loading
Figure 5.14 Utility Grid Supplied Current with Ratios, $V^{-1}/V^{+1} = 0\%$, $V^{-5}/V^{+1} = 35\%$ and $V^{-7}/V^{+1} = 20\%$ for Linear and Non-linear Loading
5.5 **Summary**

In this chapter the current components extracted by the multi-SRF proposed in Chapter 4.0 is compared to those extracted by the CPCT. Comparison is based on two conditions of the grid to which the microgrid is hooked to. The first condition is related to an ideal voltage. The second condition is associated with either supply asymmetry, distortion or both. Results verify that the multi-SRF produced components that in most cases equivalent to counterparts from CPCT. Differences were observed for a combined asymmetry/distortion coupled with linear and non-linear loads. However, these differences are apparent for high ratios of fundamental negative sequence and harmonic voltage components. Finally, the chapter concluded with application of the local FCS-MPC for GFE units to regulate extracted current components under a distorted utility grid condition.
CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this work control of power converters that interface DERs in a radial microgrid system is presented. Converter controllers have been implemented by a distributed model predictive control approach. The modes investigated in this work include grid and island operations. Conditions investigated under the grid mode, were high, low short circuit KVA levels and non-ideal grid supply. The approach for control adopted is based on individual voltage/ or current components that are relevant for a control strategy. To achieve an individual component strategy, an extraction method is required. Traditionally, current components determination has been correlated with power theories. The approach undertaken in this work is to obtain components by rotating measured stationary frame voltages and currents in synchronous reference frames.

In this work, the SRF approach is used to decompose and extract components under steady state operation of the microgrid with linear and non-linear loading effects. In addition, interfacing converter related current(s) and voltage(s) are also decomposed using this method. A mathematical model is derived for each component in the converter quantities of GF and GFE subsystems which are included in the cost function, relevant to local controller of microgrid unit.

The approach of providing per component control in microgrid units give rise to a targeted control. The control approach in this dissertation is a component to component control. Here, the controls encompasses all components in achieving the system
objective(s). Therefore, a reference setting is established for each component, voltage or current, which is related to achieving a local unit objective and eventually a global objective from a system wide prospective. This approach provides more pinpoint control. Linear based reference generation has been used where only one reference is presented to the controller that is made from weight factors of current components [102].

In this work, coordination between the various units in the microgrid is implemented via the share factors that are associated with each current component for each GFE unit that is actively connected to the PCC. One conclusion from the work presented is that PCC load current decomposition/extraction can be performed in a main microgrid control center to obtain components. These components can be communicated, with corresponding share factors, to each GFE unit using a less demanding communication system since the components appear as DC in SRF. The process of PCC voltage decomposition/extraction can be performed by local controls of each GFE unit. At the same time, a GF unit needs decomposition/extraction only at the local level (based on terminal measurements) according to the per component voltage strategy presented in Chapter 3.0 and 4.0. As presented, filter capacitor voltage and converter output current are decomposed from which fundamental/harmonic voltage and current components in positive and negative sequence are obtained for further control related processing.

Implementation wise, a per component control approach faces an obstacle. For example, in using a conventional PI controller for regulating current components in the loading conditions of Chapter 4.0 which includes 1st positive, 1st negative, 5th negative and 7th positive components, eight parameters are required to be tuned. Therefore, this work adopted a FCS-MPC that is distributed among GFE and GF units. Here, each unit is
considered a subsystem of the overall system, that is, the microgrid. Each subsystem has an associated local controller, which is responsible for satisfying the system objectives. The overall objectives of the microgrid system considered in this work are mode dependent. As presented, when a grid mode is detected, the objective of each GFE subsystem controller is to achieve a satisfactory per component current regulation such that the composite load current provided by the DER through the interfacing converter delivers (on the assumption of available capacity) its correct share. Hence this provides an overloaded utility grid with much needed power to maintain a power based capacity/demand balance. According to the results presented in this work, microgrid units can share negative sequence and harmonic current components to achieve a better power quality profile at the PCC where loads are connected.

In island mode of operation, the global objective is to eliminate frequency deviations through a power demand/generation balance. Hence, each GFE achieves this through the accurate control of each component. In this mode, the voltage controller sets the negative sequence voltage of the capacitor associated with this converter to zero by minimizing the square of the error between predicted and reference values for the linear and non-linear loading conditions as presented in Chapters 3.0 and 4.0. In linear and non-linear loading conditions of Chapter 4.0, two additional voltage error terms are included in the local cost function of the GF subsystem, these are the 5th and 7th components which are also regulated to zero. Power quality enhancement at the PCC in this work has been achieved by two ways:

1. All but the positive sequence voltage components are driven to zero, through the local controller of the GF subsystem.
2. Directly increasing the shares of negative sequence fundamental current components of GFE converters, to minimize the voltage drop, $i_{dq/g}^{-1}Z_{g/l}$, initiated from the grid/ GF converter.

Results presented in this work report significant power quality enhancement (in terms of negative sequence voltage) and good tracking performance for capacitor voltage relative to the nominal positive sequence voltage reference for unbalanced loading, where the negative sequence component rotates at $754$ rad/sec at a rotation frame of, $\omega t = -\theta$. The FCS-MPC based per component voltage controller also shows good results in tracking positive sequence voltage despite the unbalanced and non-linear loading of the PCC and even when no GFEs are switched to take any shares of fundamental negative sequence and harmonics current components. This mainly attributed to the impact of the controller in nullifying non-positive fundamental sequence voltage components.

Current related tracking which has been shown for various modes in chapters 3.0 to 5.0 proves the feasibility of the per component approach on one hand and the capability of the distributed FCS-MPC in providing adequate regulation when the cost function extends to multi-components on the other.

The final part of this dissertation is to examine where the current components obtained through the multi-SRF stand relative to the CPCT. This theory also decomposes current into components correlated with power phenomenon. Here, the CRMS are obtained, from which the time domain expressions are found so that an $abc/dq$ transform is implemented at several frames to obtain the components in SRF. Results from Chapter 5.0 present a component by component comparison between CPCT and the multi-SRF. Several loading conditions are investigated under (none) ideal utility grid voltage. Results
of components from the multi-SRF compare very well to these of the CPCT. This is even more evident when the ratios of fundamental negative sequence are low. The fundamental negative sequence is responsible for unbalanced supply voltage while harmonic components are responsible for distortion of the supply. Finally the distributed FCS-MPC has been validated under non-ideal grid mode operation where sufficient per component current regulation is observed. This leads to the conclusion that the proposed component based current control strategy is valid for all types of modes under which the microgrid subsystem operates.

6.2 Future Work

Based on the current work and results, the following are potential ideas for future work:

1. Extend the per component control approach to mesh microgrid systems. In this case any two subsystems will have strong interactions in states and inputs.

2. Perform load flow analyses based on extracted current and voltage components for the mesh topology microgrid.

3. Include subsystems with non-dispatchable sources. In this case each local FCS-MPC must include additional terms in the cost function to account for source control.

4. Investigate increasing the prediction horizon for GFE local controllers beyond 1 and the effect they produce (if any) on the response of the FCS-MPC system.

5. Determination of the share factors, used in this work, from active and reactive load flow studies carried out for a mesh topology microgrid.

6. Propose an extraction method for current components based on an extended delay signal cancellation for the case of linear and non-linear loading.
REFERENCES


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