Artificial Intelligence-based Control Methods for Optimal and Stable Operation of Converter-dominated Microgrids

Bahram Pournazarian
Artificial Intelligence-based Control Methods for Optimal and Stable Operation of Converter-dominated Microgrids

Bahram Pournazarian

A doctoral thesis completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall TU1 of the school on 31 March 2023 at 10:00.

Aalto University
School of Electrical Engineering
Department of Electrical Engineering and Automation
Renewable Energies for Power Systems Group
Supervising professor
Associate Professor Edris Pouresmaeil, Aalto University, Finland

Thesis advisor
Associate Professor Edris Pouresmaeil, Aalto University, Finland

Preliminary examiners
Professor Huai Wang, Aalborg University, Denmark
Assistant Professor Qianwen Xu, KTH Royal Institute of Technology, Sweden

Opponent
Professor Marco Liserre, Christian-Albrechts University of Kiel, Germany

Aalto University publication series
DOCTORAL THESES 13/2023

© 2023 Bahram Pournazarian

ISBN 978-952-64-1134-7 (printed)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Unigrafiia Oy
Helsinki 2023

Finland
Author
Bahram Pournazarai

Name of the doctoral thesis
Artificial Intelligence-based Control Methods for Optimal and Stable Operation of Converter-dominated Microgrids

Publisher
School of Electrical Engineering

Unit
Department of Electrical Engineering and Automation

Series
Aalto University publication series DOCTORAL THESES 13/2023

Field of research
Renewable Energies for Power Systems

Manuscript submitted 20 December 2022 Date of the defence 31 March 2023

Permission for public defence granted (date) 19 January 2023 Language English

☐ Monograph ☑ Article thesis ☐ Essay thesis

Abstract
The microgrid as a major player in future smart grids includes power-electronic-based distributed generation (DG) units, loads, energy storage system (ESS), and lines. The microgrid can operate either island or connected to the main grid. The voltage and frequency references in island microgrid are adjusted by individual DGs while in grid-connected mode these references are dictated to the DGs by the upstream grid. The droop control and virtual synchronous generator (VSG) control are well-known methodologies to control several converters in an island microgrid. The small-signal stability of a microgrid is defined as its ability to move from one permissible operating point to another permissible operating point after being subjected to a small-signal disturbance. The droop control coefficients, virtual impedances, and VSG parameters should be tuned in a feasible range to maintain the stability of microgrid.

Despite the remarkable achievements, the state-of-the-art microgrid control methods face three major challenges: (1) These methods have not optimized the virtual impedances by considering the microgrid small-signal stability and power sharing in all operating points, inappropriate application of virtual impedances can jeopardize the microgrid stability; (2) VSG provides virtual inertia and damping in the microgrid including static and dynamic loads, however, inappropriate tuning of these parameters can threaten the microgrid stability, microgrid frequency, voltage, and reactive power sharing; (3) The application of artificial neural networks in online control of converters and VSGs is necessary to fulfil the stability and dynamic performance requirements in future microgrids.

First and foremost, this thesis introduces a new perspective on microgrid control methods, which suggests to analyse the stability of all operating points and define an optimization problem according to the dynamics and stability preferences of microgrid. This optimization method concludes the stable operation of microgrid in all operating points and a desirable dynamic performance, simultaneously.

Secondly, the thesis reports a novel method to optimize the virtual inertia, virtual damping, current state-feedback factor, and virtual impedances to enhance the microgrid small-signal stability. Moreover, the reactive power sharing, frequency Nadir, and voltage of buses are enhanced.

Finally, the thesis introduces an online optimal control method based on adaptive network-based fuzzy inference system (ANFIS). In this method, the controller learns the optimal control policy for each value of active and reactive power and generates the optimal value of virtual inductance accordingly. The reactive power circulation among converters is minimized and the voltage drops on virtual inductances are negligible. Moreover, the small signal stability of microgrid is enhanced

Keywords
Adaptive network fuzzy inference systems, microgrid, particle swarm optimization, small-signal stability, virtual impedance, virtual synchronous generator


ISSN (printed) 1799-4934 ISSN (pdf) 1799-4942

Location of publisher Helsinki Location of printing Helsinki Year 2023

This research has been performed in the Renewable Energies for Power Systems Group at the Department of Electrical Engineering and Automation, Aalto University. The founding of doctoral position has been provided by Professor Edris Pouresmaeil and the funding from Business Finland under Solar X project by Professor Matti Lehtonen. I would like to warmly appreciate all the funding providers who facilitated my doctoral research.

I began the doctoral studies in November 2018 under the supervision of Professor Edris Pouresmaeil in a vibrant and productive environment. I would like to appreciate my supervisor for providing me with this great opportunity and guiding me through the doctoral research.

The collaboration and great comments from Dr. Reza Sangrody in Publications V-VII are deeply appreciated. I would like to thank Dr. Oriol Gomis-Bellmunt for valuable comments in Publication V. I would like to thank my team-mate Dr. Meysam Saeedian for the collaboration and great comments which significantly enhanced my research papers. The point-to-point review and comments from Professor Gevork B. Gharehpetian in Publication VII is warmly appreciated. I would like to warmly thank Professor Jorma Kyyrä for the guidance and support during my doctoral studies.

Moreover, I would like to appreciate my former colleagues and department staff for the kind support and help during this journey and providing a nice research atmosphere. I would like to thank particularly Dr. Meysam Saeedian, Dr. Mahdi Pourakbari Kasmaei, and Dr. Kourosh Latifi for all their support and guidance. Finally, I am grateful to my family for their endless support and patience during this stage of my life: my mother, my father, my siblings, and lovely nephews and nieces.

Espoo, January 25, 2023,

Bahram Pournazarian
Contents

Preface ........................................ 5

Contents ...................................... i

List of Publications .......................... iii

Author's Contribution ...................... v

Abbreviations ............................... vii

Symbols ...................................... ix

1. Introduction ............................... 1
   1.1 Background .................................. 1
   1.2 Research objectives ....................... 2
   1.3 Contributions to the research field ....... 3
   1.4 Structure of the thesis .................... 4

2. Review of relevant literature .......... 5
   2.1 Microgrid small-signal stability analysis .... 5
      2.1.1 Eigenvalues analysis ................... 5
      2.1.2 Eigenvalues participation analysis ....... 6
      2.1.3 The state of the art in microgrid stability analysis 6
   2.2 VSG control methods ...................... 8
      2.2.1 Swing equation ....................... 8
      2.2.2 Tuning of VSG parameters ............... 8
   2.3 Virtual impedances analysis and tuning ... 9
   2.4 Artificial intelligence and PSO algorithm applications ... 10

3. Optimization approaches for droop-based microgrids 13
   3.1 PSO-based droop control of converters .......... 13
      3.1.1 Power calculator and LPF ................. 13
      3.1.2 Droop control .......................... 13
      3.1.3 Virtual impedances ...................... 14
## Contents

3.1.4 PLL model ........................................ 14
3.1.5 Voltage controller ................................. 15
3.1.6 Reference frame transformation ................. 15
3.1.7 The optimization flowchart ...................... 16

3.2 ANFIS-based droop control of converters .......... 17
  3.2.1 The control block diagram ..................... 18
  3.2.2 The objective function .......................... 18
  3.2.3 The training of ANFIS networks .............. 19

4. Optimization approaches for VSG-based microgrids 23
  4.1 PSO-based VSG control of microgrids supplying static loads 23
    4.1.1 VSG controller ................................ 23
    4.1.2 Voltage controller ............................. 23
  4.2 PSO-based VSG control of microgrids supplying SIM ... 26
    4.2.1 Optimization algorithm to draw the optimal parameters .......... 26

5. Results and Discussion 31
  5.1 Optimization approaches for droop-based microgrids ... 31
    5.1.1 PSO-based droop control of converters .......... 31
    5.1.2 ANFIS-based droop control of converters ....... 36
  5.2 Optimization approaches for VSG-based microgrids ... 42
    5.2.1 PSO-based VSG control of microgrids supplying static loads ................. 42
    5.2.2 PSO-based VSG control of microgrids supplying SIM 46

6. Conclusions and outlook 53
  6.1 Conclusions ........................................ 53
  6.2 Outlook ............................................ 55

References 57

Publications 65

Errata 123
This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.


Author’s Contribution

Publication I: “Microgrid Frequency & Voltage Adjustment Applying Virtual Synchronous Generator”

The author suggests an advanced voltage and frequency control and grid-synchronisation strategy for VSG-based microgrids consisting of several converters.

Publication II: “Virtual Impedances Optimization to Enhance Microgrid Small-Signal Stability and Reactive Power Sharing”

The author proposes a novel droop-based control method which utilizes the PSO algorithm and a new objective function to draw the optimal virtual impedances at all operating points. The proposed optimization algorithm aims at maximizing the microgrid stability index while keeping the reactive power mismatches at minimum level.


The author examines the effect of current state-feedback factor \( (F) \) on small-signal stability and dynamic response of droop-controlled microgrids and proposes an optimal value for it.
Publication IV: “Feasible Ranges of Microgrid Parameters Based on Small-signal Stability Analysis”

The author introduces the dynamic model of a microgrid including PLL, VI, current state-feedback factor (F), and SIM and scrutinizes the permissible ranges of virtual impedances and droop coefficients.


The author proposes a novel ANFIS-based optimization method for online tuning of virtual inductances in the island microgrids. The proposed objective function (OF) minimizes the reactive power mismatches and improves microgrid stability in different load levels.

Publication VI: “Simultaneous Optimization of Virtual Synchronous Generators (VSG) Parameters in Island Microgrids Supplying Induction Motors”

The author proposes a generalized small-signal stability analysis framework for an island microgrid including arbitrary number of VSGs, lines, static and dynamic loads. Subsequently, the effect of SIM load on permissible ranges of virtual impedances is analyzed. Finally, the author suggests a novel PSO-based optimization platform to draw optimal virtual impedances, J, D and F to enhance the microgrid stability, minimize the voltage drops, minimize reactive power mismatches, and enhance the point of minimum frequency (Nadir), simultaneously.

Publication VII: “Simultaneous Optimization of Virtual Synchronous Generators Parameters and Virtual Impedances in Islanded Microgrids”

The author draws the permissible ranges of J, D from the small-signal stability point of view. The author proposes an optimization method and a fractional objective function to calculate VSG parameters and virtual impedances in islanded microgrids. The proposed method outperforms the conventional droop control and VSG control methods to reinforce the small-signal stability of the microgrid, decrease the current overshoot and minimize the reactive power mismatches.
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANN</td>
<td>Artificial neural network</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>ANFIS</td>
<td>Adaptive network fuzzy inference system</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed generation</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DM</td>
<td>Data matrix</td>
</tr>
<tr>
<td>EI</td>
<td>Eigenvalues index</td>
</tr>
<tr>
<td>ESS</td>
<td>Energy storage system</td>
</tr>
<tr>
<td>FIS</td>
<td>Fuzzy inference system</td>
</tr>
<tr>
<td>HVDC</td>
<td>High voltage direct current</td>
</tr>
<tr>
<td>iPOD</td>
<td>Intelligent power oscillation damper</td>
</tr>
<tr>
<td>LPF</td>
<td>Low-pass filter</td>
</tr>
<tr>
<td>MFs</td>
<td>Membership functions</td>
</tr>
<tr>
<td>MPC</td>
<td>Model predictive control</td>
</tr>
<tr>
<td>Nadir</td>
<td>Point of minimum frequency</td>
</tr>
<tr>
<td>OF</td>
<td>Objective function</td>
</tr>
<tr>
<td>PM</td>
<td>Participation matrix</td>
</tr>
<tr>
<td>pv</td>
<td>Participation vector</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle swarm optimization</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-locked loop</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of common coupling</td>
</tr>
<tr>
<td>PSS</td>
<td>Power system stabilizer</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>PBDG</td>
<td>Power electronic-based distributed generation</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional integral</td>
</tr>
<tr>
<td>RoCoF</td>
<td>Rate of change of frequency</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable energy sources</td>
</tr>
<tr>
<td>RL</td>
<td>Resistive inductive load</td>
</tr>
<tr>
<td>SIM</td>
<td>Symmetrical induction motors</td>
</tr>
<tr>
<td>SI</td>
<td>Stability index</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage source converter</td>
</tr>
<tr>
<td>VSG</td>
<td>Virtual synchronous generator</td>
</tr>
<tr>
<td>VI</td>
<td>Virtual impedances</td>
</tr>
</tbody>
</table>
Symbols

\[ A_{MG} \]  \quad \text{State matrix of microgrid}

\[ D \]  \quad \text{Virtual damping}

\[ F \]  \quad \text{Current state-feedback factor}

\[ f_1 \]  \quad \text{Personal learning coefficient in PSO}

\[ f_2 \]  \quad \text{Global learning coefficient in PSO}

\[ I_m \]  \quad \text{Imaginary part of a complex number}

\[ i_{\text{LineDQ}} \]  \quad \text{Line current components in common } dq \text{-frame}

\[ \Delta i_{\text{LineDQ}} \]  \quad \text{First order derivative of } \Delta i_{\text{LineDQ}} \text{ with respect to time}

\[ i_{\text{LoadDQ}} \]  \quad \text{Load current components in common } dq \text{-frame}

\[ \Delta i_{\text{LoadDQ}} \]  \quad \text{First order derivative of } \Delta i_{\text{LoadDQ}} \text{ with respect to time}

\[ i_{ld} \]  \quad \text{d-axis terminal current of converter}

\[ i_{iq} \]  \quad \text{q-axis terminal current of converter}

\[ J \]  \quad \text{Virtual inertia}

\[ K_f \]  \quad \text{droop coefficient of VSG}

\[ k_{pv} \]  \quad \text{Proportional coefficient of PI in voltage controller}

\[ k_{ic} \]  \quad \text{Integral coefficient of PI in current controller}

\[ k_{pc} \]  \quad \text{Proportional coefficient of PI in current controller}

\[ k_{iv} \]  \quad \text{Integral coefficient of PI in voltage controller}

\[ m \]  \quad \text{Number of microgrid eigenvalues}

\[ M_{OF}^{(k+1)}_i \]  \quad \text{The minimum } OF \text{ value experienced by } i^\text{th} \text{ particle in } (k+1)^\text{th} \text{ iteration}

\[ M_{OF}^{(k+1)}_{\text{best}} \]  \quad \text{The minimum } OF \text{ value experienced by all particles in } (k+1)^\text{th} \text{ iteration}

\[ m_p \]  \quad \text{Active power droop coefficient}

\[ n \]  \quad \text{Number of operating points}

\[ n_q \]  \quad \text{Reactive power droop coefficient}

\[ n_{Pop} \]  \quad \text{Population size (swarm size) in PSO}

\[ P \]  \quad \text{Active power}
Symbols

\( p \) Instantaneous active power
\( P_0 \) Reference active power
\( p_{vi} \) \( i^{th} \) participation vector
\( Q \) Reactive power
\( q \) Instantaneous reactive power
\( Q_0 \) Reference reactive power
\( r_1 \) Random value \( 0 < r_1 < 1 \)
\( r_2 \) Random value \( 0 < r_2 < 1 \)
\( Re \) Real part of a complex number
\( s \) Number of power electronics sources in microgrid
\( t \) Time
\( v_i^{(k+1)} \) The velocity of particle in \((k+1)^{th}\) iteration in PSO
\( v_{oq,n} \) Nominal q-axis voltage
\( V_{i,\text{min}} \) Lower bound of \( i^{th} \) particle’s velocity
\( V_{i,\text{max}} \) Upper bound of \( i^{th} \) particle’s velocity
\( v_{od,f} \) d-axis input voltage to the PLL after its low-pass filter
\( v_{od,f}^{\prime} \) First order derivative of \( v_{od,f} \) with respect to time
\( w \) Inertia weight in PSO
\( x_{\text{INV}} \) States variables of inverter
\( \Delta x_{\text{INV}} \) First order derivative of \( x_{\text{INV}} \) with respect to time
\( y_i^{(k+1)} \) The location of particle in \((k+1)^{th}\) iteration in PSO
\( y_{i,\text{min}} \) Lower bound of \( i^{th} \) particle’s location
\( y_{i,\text{max}} \) Upper bound of \( i^{th} \) particle’s location
\( \lambda \) Velocity limitation coefficient
\( \beta \) Arbitrary weighting coefficient
\( \gamma_d \) Auxiliary variable in d-axis
\( \gamma_d^{\prime} \) First order derivative of \( \gamma_d \) with respect to time
\( \gamma_q \) Auxiliary variable in q-axis
\( \gamma_q^{\prime} \) First order derivative of \( \gamma_q \) with respect to time
\( \delta_{\text{com}} \) The angle of local \( dq \)-frame with respect to common \( dq \)-frame
\( \zeta \) Damping ratio of an eigenvalue
\( \phi \) Right eigenvector
\( \phi_{\text{PLL}} \) First order derivative of phase-locked loop angle with respect to time
\( \varphi_d \) Auxiliary variable in d-axis
\( \varphi_d^{\prime} \) First order derivative of \( \varphi_d \) with respect to time
\( \varphi_q \) Auxiliary variable in q-axis
\( \varphi_q^{\prime} \) First order derivative of \( \varphi_q \) with respect to time
Symbols

$\psi$  
Left eigenvector

$\omega^*$  
Reference angular frequency of microgrid

$\dot{\omega}^*$  
First order derivative of $\omega^*$ with respect to time

$\omega_m$  
Reference angular frequency of VSG
1. Introduction

1.1 Background

The global warming, ever-increasing electricity demand, and energy crisis necessitates the transition from conventional synchronous generator-fed power systems to the renewable energy-fed power systems. This substantial transition brings about some challenges e.g. lower grid inertia, more frequency deviations, and power system instability. A microgrid as a vital building block for modern power systems includes distributed generations (DGs), energy storage systems (ESS), and loads which can operate either islanded or grid-connected [1]. The weak power sharing, frequency deviations, zero intrinsic inertia of converters, and renewable power intermittency make the microgrids vulnerable to instability [2].

The microgrid small-signal stability is defined as the capability of microgrid to move from one equilibrium point to another operating point after a disturbance, while the state variables (e.g., voltage, frequency, etc.) remain within permissible intervals [3, 4]. However, the stability status of microgrid, power sharing, and voltage and frequency control depend strictly to the microgrid control method [5, 6].

Two major control methods; (1) droop control [7], (2) virtual synchronous generator (VSG) [8], have been proposed for controlling multiple converters in a microgrid.

The conventional droop control assigns the voltage and frequency references for multiple converters based on instantaneous reactive and active power values, however it can not share the reactive power fairly and the small-signal stability depends strictly on the droop coefficients and control parameters. The virtual impedances have been proposed to facilitate the precise reactive power sharing [9, 10]. However, the improper application and tuning of virtual impedances considering one operating point can jeopardize the microgrid stability and lead to inappropriate power sharing. The current state feedback has been used in conventional droop control [3],
but the permissible range and its optimal value have not been scrutinized.

On the other hand, the virtual synchronous generator (VSG) control method has been introduced to imitate the virtual inertia and virtual damping to power-electronics converters [8, 11]. However, the available VSG control methods have not considered the stability at all operating points and fail to enhance reactive power sharing and frequency Nadir, simultaneously [12].

The off-line optimization algorithms with different objective functions have been applied to tune the virtual impedances and control parameters of droop and VSG control methods [13, 14, 15]. However, the application of these methods is limited because of running time and required communication links. Moreover, these methods fail to consider the small-signal stability of microgrid at all operating points and the frequency Nadir while tuning the virtual impedances. This can lead to microgrid instability at some operating points.

The application of ANFIS in tuning of generalized controllers which are trained by available data has been a breakthrough [16]. The ANFIS-trained controllers can be used in online tuning of virtual impedances and control parameters of microgrids.

1.2 Research objectives

The objective of this thesis is to develop and propose intelligent control methods for islanded microgrids. The research has been categorized into (1) droop-based control of microgrids; and (2) VSG-based control of microgrids. The research has been focused on the PSO-based control methods and ANFIS-based control method. The PSO-based methods are proposed for off-line droop or VSG control of converters while the ANFIS-based method is proposed for online droop control of converters in microgrid. In summary, the following research questions are addressed:

1. In traditional small-signal stability analysis, one operating point is considered to assess the stability around it. Can a microgrid stability index be defined considering all eigenvalues in all operating points? And more importantly, how can this stability index be used in tuning of the virtual impedances?

2. How the current state feedback affects the eigenvalues of an islanded microgrid? Could an optimal value be obtained for it?

3. Can a multi-objective PSO objective function outperform a fractional objective function to achieve the microgrid stability, fair reactive power sharing, and better frequency Nadir?
4. Since the traditional optimization methods (e.g. PSO, genetic algorithm, etc.) are time-consuming and they are used as off-line tools, how can an intelligent ANFIS-based droop control method be designed in conjunction with this off-line optimization algorithms?

1.3 Contributions to the research field

The contributions of this thesis are summarized as follows:

Publication I suggests an advanced VSG control method including grid-synchronisation mechanism for voltage and frequency control of VSG-based microgrids.

In Publication II a novel droop-based control method is proposed which utilizes the PSO algorithm and a new objective function to tune the optimal virtual impedances at all operating points in order to maximize the microgrid stability index while minimizing the reactive power mismatches.

Publication III examines the effect of current state-feedback factor \( F \) on small-signal stability and dynamic response of droop-controlled microgrids and proposes an optimal value for it.

Publication IV introduces the comprehensive dynamic model of an islanded microgrid and concludes the permissible ranges of virtual impedances and droop coefficients.

Publication V proposes a novel ANFIS-based optimization method for online tuning of virtual inductances in the island microgrids. The proposed objective function \( OF \) minimizes the reactive power mismatches and improves microgrid stability in different load levels.

Publication VI proposes a generalized small-signal stability analysis framework for islanded microgrids including arbitrary number of VSGs and subsequently suggests a novel PSO-based optimization algorithm to optimize virtual impedances, \( J \), \( D \) and \( F \) to enhance the microgrid stability, minimize the voltage drops and reactive power mismatches, and enhance the point of minimum frequency \( \text{Nadir} \), simultaneously.

Publication VII proposes an optimization method and a fractional objective function to calculate optimal VSG parameters and virtual impedances in the islanded microgrid. The proposed method outperforms the conventional droop control and VSG control methods to reinforce the small-signal stability of the microgrid, decrease the current overshoot and minimize the reactive power mismatches.
1.4 Structure of the thesis

The thesis is organized as follows. Chapter 2 reviews the relevant literature including necessary concepts and the state of the art for the dissertation. Chapter 3 introduces optimization approaches for droop-based microgrids. Chapter 4 presents optimization approaches for VSG-based microgrids. Chapter 5 discusses the application of the proposed methods and results. Finally, Chapter 6 concludes the thesis and sketches the future outlook.
2. Review of relevant literature

This chapter illustrates the main concepts which are dealt with in this dissertation and categorizes the state of the art in these fields. Firstly, the key points regarding the small-signal stability analysis of microgrid are covered. Next, the concept of virtual synchronous generator is elaborated. Lastly, the application of artificial intelligence and optimization algorithms in control of converters is reviewed.

2.1 Microgrid small-signal stability analysis

2.1.1 Eigenvalues analysis

Traditionally, the state-space matrices of a microgrid as a non-linear dynamic system are drawn and linearized around an operating point [3]. Using virtual resistor idea, the outputs of microgrid are expressed in terms of state-variables, consequently, the system is explained by a simple state equation as follows [3, 5].

\[
\begin{bmatrix}
\Delta x_{\text{INV}} \\
\Delta i_{\text{LineDQ}} \\
\Delta i_{\text{LoadDQ}}
\end{bmatrix}
= A_{MG}
\begin{bmatrix}
\Delta x_{\text{INV}} \\
\Delta i_{\text{LineDQ}} \\
\Delta i_{\text{LoadDQ}}
\end{bmatrix}
\] (2.1)

The eigenvalues of the system matrix ($A_{MG}$) are drawn using `eig()` command in MATLAB [6]. The microgrid is stable if all eigenvalues have negative real-parts [7]. However, a microgrid which has a zero eigenvalue and all the other eigenvalues have negative real-parts is still known to be asymptotically stable [3, 5]. The damping ratio of an eigenvalue is calculated by Equation (2.2).

\[
\zeta(Z = Re + j.Im) = \frac{|Re|}{\sqrt{Re^2 + Im^2}}
\] (2.2)
2.1.2 Eigenvalues participation analysis

A participation analysis can illustrate which state variables affects a certain mode dominantly. A participation matrix (PM) is defined for all states which has been well-explained in [3, 7]. Considering the right and left eigenvectors as \( \phi \) and \( \psi \), PM is defined as follows.

\[
PM = \begin{bmatrix}
pv_1 & pv_2 & \ldots & pv_m
\end{bmatrix}
\]  
(2.3)

where the \( i^{th} \) participation vector (pv) is defined as follows.

\[
pv_i = \begin{bmatrix}
pv_{1i} & \ldots & pv_{mi}
\end{bmatrix}^T = \begin{bmatrix}
\phi_{i1}, \psi_{i1}, \ldots, \phi_{mi}, \psi_{im}
\end{bmatrix}^T
\]  
(2.4)

where \( pv_{mi} \) represents the effect of \( m^{th} \) state variable on \( i^{th} \) mode [7].

2.1.3 The state of the art in microgrid stability analysis

A distributed framework for small-signal stability analysis of a microgrid has been proposed in [17] which reconstructs the system dynamic Jacobian matrix based on the data received from neighborhood buses and local data. The optimized dynamic droop control in [18] has enhanced the microgrid small-signal stability and power sharing capability. The small-signal modeling of VSG has been performed in [19] and the bandwidth of power loop has been optimized to avoid voltage distortions. The small-signal model of parallel droop-controlled inverters has been developed in [20] based on terminal characteristics of inverters.

The small-signal stability analysis of microgrid clusters, the coupling among microgrids and different control layers, and the optimization of distributed control parameters have been performed in [21]. The fundamental framework for microgrid small-signal stability analysis under distributed control has been introduced in [22]. The small-signal stability analysis of a microgrid including two forms of non-linear loads (ideal constant power load and motor drive system) has been developed in [23]. The Popov’s absolute stability theorem has been used in [24] to evaluate the stability of an AC microgrid supplying constant power loads.

Moreover, the VSG optimization method in [25] aims to present a smooth transition in response to a large-signal disturbance, limit the voltage angle deviations, and improve the transient stability of microgrid. The stability region of a droop-controlled distributed generation in autonomous microgrid has been estimated by Ridge Regression Method in [26]. The small-signal modeling and stability analysis of a microgrid under harmonic conditions (supplying non-linear loads) has been performed in [27]. A new small-signal modeling method based on characteristic equation of converter-based AC microgrids has been proposed in [28] which excels the conventional state-space-based approach.
The impact of reactive power droop gain on small-signal stability of microgrid has been analyzed in [29] to draw the stability chart of a microgrid. It has been suggested that cascading lead compensators in series with real power-frequency droop control could enhance the microgrid stability margin [30]. A distributed secondary optimal control method has been proposed in [31] to enhance microgrid stability and dynamic performance. It has been proposed that adding a branch of multiple DGs in microgrid topology could potentially deteriorate the stability and therefore the microgrid expansion should be performed carefully [32].

The analyzes of active load effects on microgrid stability have been performed in [33] and an optimal control method excluding PLL has been proposed which minimizes the DC voltage and active power errors. The stability region of an AC microgrid supplying different static loads and induction motors has been concluded by bifurcation analysis in [34]. The optimum ranges of key control parameters of a droop-controlled microgrid have been drawn by small-signal stability analysis in [35]. The effects of equal and unequal power sharing on dynamic stability of a hybrid microgrid have been scrutinized in [36] and a stability domain has been drawn accordingly.

However, the possibility of a tradeoff between faster load sharing and microgrid stability has been reported and a power system stabilizer (PSS) has been proposed to deal with low-frequency oscillations [37]. The reduced order small-signal modeling and stability analysis of a grid-tied microgrid has been developed by singular perturbation technique in [38]. The impacts of reconfiguration and network array (meshed or radial) on small-signal stability margin of islanded droop-controlled microgrid has been evaluated in [39]. An efficient and accurate reduced-order modeling of inverter-based microgrids has been proposed in [40]. The dynamic response and stability of a microgrid controlled by single-loop and multi loop droop control methods have been compared in [41]. The small-signal stability has been examined by Lyapunov’s first method in this dissertation (Publication VII). The small-signal stability of a non-linear system is examined by the eigenvalues locations:

1. When the eigenvalues have negative real parts, the original system is asymptotically stable.

2. When at least one of the eigenvalues has a positive real part, the original system is unstable.

3. When the eigenvalues have real parts equal to zero, it is not possible on the basis of the first approximation to say anything in general.

Since the islanded MG has one zero eigenvalue ([3]-[6]), it is asymptotically
stable if the first and second conditions are met.

2.2 VSG control methods

2.2.1 Swing equation

The idea to imitate the dynamic behavior of synchronous generators to add virtual inertia and virtual damping to the conventional inertia-less converters has been the backbone of almost all VSG control methods [8, 9, 10, 11]. The VSG plays the role of conventional droop control block, but the swing equation is applied instead [42]. A comparison between dynamic characteristics of VSG and conventional droop control is well-illustrated in [43]. An advanced VSG structure can resolve the power oscillation issues in a microgrid with a considerable portion of converter-based generations [44].

The conventional swing equation determines the reference frequency of VSG according to Equation (2.5) applying virtual inertia ($J$) and virtual damping ($D$). The reference angle of voltage can be drawn by an integration as it is seen in Equation (2.6).

\[
\begin{align*}
    P_{in} - P_{out} &= J \omega_m \frac{d \omega_m}{dt} + D (\omega_m - \omega_{PLL}) \\
    \delta &= \int \omega_m dt
\end{align*}
\]

(2.5)

(2.6)

where $P_{in}$, $P_{out}$, $\omega_m$ are input power to VSG, output electrical power of VSG, and reference frequency of VSG, respectively.

2.2.2 Tuning of VSG parameters

The tuning of VSG parameters should ensure that the eigenvalues of the system locate in the stable region [45]. The dynamic performance of VSG such as active power overshoot and response time can be optimized through adaptive tuning of $J$ and $D$ [46]. It has been reported that self-tuned VSG can minimize the amplitude and rate of change of frequency (RoCoF) in autonomous microgrids and consequently enhance the frequency stability [47].

A synchronverter is a grid-connected VSG which mimics the conventional synchronous generator [48]. It is suggested that removing the synchronization unit (PLL) can decrease the computational burden and enhance the frequency regulation and active and reactive power control of synchronverter [49]. Moreover, removing the PLL has been proposed to avoid the effects on VSG dynamics [50]. The improved synchronverter in [51] keeps the voltage and frequency in the permissible ranges and
the stable operation of synchronverter is analytically verified. Applying fuzzy-secondary-controller for voltage and frequency regulation of VSGs has enhanced the performance of them compared to conventional VSGs [52].

The application of synchronous generator emulation control has been extended to VSC-HVDC stations [53]. An upgraded method to tune the parameters of a synchronverter augmented with a correction-loop has been proposed in [54] which enhances the transient and steady-state responses. The application of consensus-based method in secondary droop control of VSGs has been scrutinized in [55] inside a distributed framework. The damping effect of a VSG with alternating inertia could support the transient stability of nearby machines as reported in [56]. Moreover, an adaptive virtual inertia control method based on bang-bang control strategy has been proposed to reduce the dynamic frequency deviation and improve the frequency stability of microgrid [57]. An improved active and reactive power decoupling mechanism has been proposed for VSGs in microgrid which is more stable than conventional methods [58].

2.3 Virtual impedances analysis and tuning

The application of virtual impedances could deal with power coupling issue and enhance the stability of microgrid. A robust virtual impedance implementation method has been proposed to decrease the voltage deviations caused by harmonic loads [59]. A reactive power sharing strategy applying adaptive complex virtual impedances has been proposed for autonomous microgrids [60]. A reactive power sharing strategy using virtual impedances to compensate voltage drop mismatches across the feeders has been introduced in [61]. This method utilizes a communication link among DGs in island microgrid.

Another improved reactive power sharing scheme using the new concept of virtual-output-impedance-based droop control has been introduced for multi-bus radial microgrids [62]. However, the accurate active and reactive power sharing in a meshed microgrid structure has been achieved by adaptive regulation of virtual impedances [63]. It has been suggested that the application of virtual impedances inside an improved droop control strategy can change the line characteristics and consequently alleviate the coupling between voltage and frequency [64].

A novel voltage stabilization and power sharing control using virtual complex impedance has been developed in [65] which improves the voltage quality and it is not vulnerable to changes in hardware parameters. A coordinated virtual impedance tuning methodology has been proposed in [66] to enhance the microgrid stability and compensate for impedance mismatches.
The application of virtual admittance loop has been introduced in [67] to alleviate the voltage harmonics in an unbalanced microgrids including parallel current-controlled converters.

2.4 Artificial intelligence and PSO algorithm applications

The double artificial neural network (ANN) can be used to design the virtual inertia of VSG considering stability and reliability [68]. A fuzzy secondary controller has been proposed in [69] to tune the virtual impedances of VSG adaptively and a proportional reactive power sharing has been realized, consequently. A data-driven optimal control strategy based on reinforcement learning has been developed in [70] to adaptively adjust virtual inertia and damping of VSG. An ANN has been applied to VSG to adjust virtual inertia aimed at improving the VSG response and alleviating the frequency overshoot [71].

A novel control strategy combining fuzzy control and model predictive control (MPC) has been proposed to adjust virtual inertia and virtual damping online and minimize the frequency deviations [72]. The application of finite control set MPC in inner loop of VSG has led to faster dynamic response, simple control structure, and enhanced stability [73]. A novel MPC-based VSG control has been proposed for ESS which enhances the voltage and frequency of island microgrid [74]. The quantitative feedback theory is applied to adjust the VSG parameters so as the system robust stability and performance are satisfactory [75].

However, an extended VSG control combining the concepts of virtual rotor, virtual primary, and virtual secondary control has been proposed in [76] for robust tuning of virtual parameters aimed to regulate the system frequency. An adaptive ANFIS-based add-on controller has been proposed in [77] to draw the reference current for an inner current control loop in VSC. An intelligent power oscillation damper (iPOD) has been developed for grid-forming converters using artificial intelligence ensemble model called Random Forests and this iPOD damps the electromechanical inter area power oscillations [78]. It has been reported that the pattern recognition capability of ANFIS can be applied to detect islanding of microgrid [79].

However, the PSO algorithm has been firstly proposed to deal with the optimization of continuous nonlinear functions [80]. Recently, the PSO has been applied to a wide range of optimization problems in electric power systems [81].

Moreover, an advanced PSO-based method has been proposed in [82] to enhance the bus voltage, frequency stability, system frequency, and microgrid stability under optimized droop control. The optimal design of LC filter, control parameters, and damping resistance of grid-connected converters have been achieved in [83], while the controller parameters
and sharing coefficients in island mode of operation have been optimized. The new load-flow analysis in [84] has been proposed for droop-controlled microgrids and the PSO is used to optimize droop parameters such that the reactive power sharing, voltage regulation, and microgrid stability are fulfilled.

The application of PSO in online minimization of harmonic distortion of a droop-controlled island microgrid has been concluded in [85]. The proposed novel droop control with coupling compensation and inertia in [86] has used PSO algorithm to optimize the coupling compensation and inertia which has enhanced the dynamic performance and stability of DGs. A hybrid algorithm including PSO and salp swarm inspired algorithm has been suggested in [87] for optimal design of droop control which has a self-refining mechanism; it means the algorithm parameters are refined adaptively according to the optimization problem.
3. Optimization approaches for droop-based microgrids

In this chapter two control methods are proposed; the PSO-based droop-control of converters (Publication II, Publication III), and ANFIS-based droop control of converters (Publication V).

3.1 PSO-based droop control of converters

The block diagram of the proposed optimal controller is demonstrated in Fig. 3.1. This method has been explained in (Publication II) and the small-signal stability of an upgraded model including current state-feedback has been elaborated in (Publication III). The dynamic models of the blocks in the proposed diagram are explained herein.

3.1.1 Power calculator and LPF

The instantaneous active and reactive powers (p and q, respectively) are calculated by Equations (3.1), (3.2). Moreover, these power components pass through a LPF with a specific cut-off frequency ($\omega_c$). The active and reactive powers (P and Q, respectively) are finally drawn as the outputs of LPF.

\[
p = \frac{3}{2}(v_{od}.i_{od} + v_{oq}.i_{oq}) \Rightarrow P = \frac{\omega_c}{s + \omega_c} \cdot P, \quad (3.1)
\]

\[
q = \frac{3}{2}(v_{oq}.i_{od} - v_{od}.i_{oq}) \Rightarrow Q = \frac{\omega_c}{s + \omega_c} \cdot Q, \quad (3.2)
\]

3.1.2 Droop control

The reference frequency and q-axis voltage of converter are calculated by droop Equations (3.3) and (3.4), respectively.

\[
\omega^* = \omega_n - m_p \cdot P \quad (3.3)
\]
Figure 3.1. The optimal control of converter in island microgrid.

\[ v_{oq}^* = v_{oq,n} - n_q Q - V_{vir} \]  (3.4)

where \( m_p, v_{oq,n}, n_q, \) and \( V_{vir} \) are active power droop coefficient, nominal q-axis voltage, reactive power droop coefficient, and the voltage drop on virtual impedances, respectively.

### 3.1.3 Virtual impedances

The virtual impedances cause a voltage drop proportional to the output \( dq \)-currents. This voltage drop is calculated by (3.5).

\[ V_{vir} = R_v i_{oq} + X_v i_{od} \]  (3.5)

where \( R_v, X_v \) are virtual resistance and virtual reactance, respectively.

### 3.1.4 PLL model

A PLL is added to the converter to measure the angle of voltage and frequency of microgrid. The \( d \)-axis voltage passes through a LPF with the cut-off frequency of \( \omega_{c, PLL} \) (3.6) and then a PI controller forces this voltage to zero (3.7)-(3.9) to draw the angle of voltage. The angle of voltage is simply calculated by an integration on frequency (3.10) [5].

\[ v_{od,f} = \frac{\omega_{c, PLL}}{s + \omega_{c, PLL}} v_{od} \]  (3.6)
Optimization approaches for droop-based microgrids

\[ v_{od,f} = \omega_{c,PLL}v_{od} - \omega_{c,PLL}v_{od,f} \]  
\[ \dot{\phi}_{PLL} = -v_{od,f} \]  
\[ \omega_{PLL} = \omega_n - k_pPLL.v_{od,f} + k_iPLL.\phi_{PLL} \]  
\[ \delta_{PLL} = \int \omega_{PLL} dt \]  

3.1.5 Voltage controller

The current references in \(dq\)-frame are provided by voltage controller as it is seen in Equations (3.11), (3.12). The parameters \(k_{pv}, k_{iv}, \omega_{PLL}, \omega^*, \gamma_d, \) and \(\gamma_q\) are proportional coefficient, integral coefficient, PLL frequency, reference frequency, auxiliary variable in d-axis, and auxiliary variable in q-axis, respectively.

\[ \dot{\phi}_d = \omega_{PLL} - \omega^* \Rightarrow i_{ld}^* = k_{iv}.\phi_d + k_{pv}.\phi_d \]  
\[ \dot{\phi}_q = v_{oq}^* - v_{oj} \Rightarrow i_{iq}^* = k_{iv}.\phi_q + k_{pv}.\phi_q \]  

The voltage references in \(dq\) reference frame are generated by current controller as it is seen in Equations (3.13), (3.14). The parameters \(k_{pc}, k_{ic}, \omega_n, \gamma_d, \) and \(\gamma_q\) are proportional coefficient, integral coefficient, nominal frequency, auxiliary variable in d-axis, and auxiliary variable in q-axis, respectively.

\[ \dot{\gamma}_d = i_{ld}^* - i_{ld} \Rightarrow v_{id}^* = -\omega_n.L_f.i_{iq} + k_{ic}.\gamma_d + k_{pc}.\dot{\gamma}_d \]  
\[ \dot{\gamma}_q = i_{iq}^* - i_{iq} \Rightarrow v_{iq}^* = -\omega_n.L_f.i_{ld} + k_{ic}.\gamma_q + k_{pc}.\dot{\gamma}_q \]  

3.1.6 Reference frame transformation

The \(abc\) to \(dq\) transformation and vice versa

The three-phase balanced currents and voltages pass through \(abc\) to \(dq\) transformation and on the other hand, \(v_{i,dq}^*\) requires a \(dq\) to \(abc\) transformation before entering the PWM unit. The former transformation is simply explained by Equation (3.15) and the latter is written in Equation (3.16) assuming the system to be balanced three-phase.

\[ \begin{bmatrix} v_{od} \\ v_{oj} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\delta_{PLL}) & \cos(\delta_{PLL} - 2\pi/3) & \cos(\delta_{PLL} + 2\pi/3) \\ -\sin(\delta_{PLL}) & -\sin(\delta_{PLL} - 2\pi/3) & -\sin(\delta_{PLL} + 2\pi/3) \end{bmatrix} \begin{bmatrix} v_{oa} \\ v_{ob} \\ v_{oc} \end{bmatrix} \]
The local to common transformation and vice versa

The small-signal stability of microgrid is analyzed in a common $dq$ reference frame (typically named as $DQ$ frame). The detailed explanation of this concept can be found in [3, 5]. However, the following transformations are used to transform the local variables (currents and voltages) of non-reference converters or VSGs to common values. An angle is defined for any converter or VSG (except converter 1 or VSG 1) which can be seen in Fig. 3.2. The $dq$ reference frame of converter 1 or VSG 1 is chosen as $DQ$ frame which rotates at the speed of $\omega_{com}$. The currents of transmission lines and loads are already calculated in $DQ$ frame.

$$\begin{bmatrix} v_{bd} \\ v_{bq} \end{bmatrix} = \begin{bmatrix} \cos(\delta_{com}) & \sin(\delta_{com}) \\ -\sin(\delta_{com}) & \cos(\delta_{com}) \end{bmatrix} \begin{bmatrix} v_{bD} \\ v_{bQ} \end{bmatrix}$$  \hspace{1cm} (3.17)

$$\begin{bmatrix} i_{oD} \\ i_{oQ} \end{bmatrix} = \begin{bmatrix} \cos(\delta_{com}) & -\sin(\delta_{com}) \\ \sin(\delta_{com}) & \cos(\delta_{com}) \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix}$$  \hspace{1cm} (3.18)

![Figure 3.2. The angle between local and common $dq$ frames.](image)

### 3.1.7 The optimization flowchart

The proposed virtual impedance design is performed by flowchart of Fig.3.3 which includes following steps:

1. Initialization of the optimization variables within the stable interval of any variable. These intervals are drawn by eigenvalues analysis.
2. The number of PSO particles, iterations, and the other parameters of the algorithm are initialized and the PSO algorithm is started.

3. The load-flow analysis is run in the specified time interval ([0, t]) by MATLAB (ode23s command) and several operating points are extracted. The number of operating points depends on the solver time step and total time of simulation.

4. The eigenvalues stability analysis is performed for operating point \( x_i \) to check the stability status of microgrid.

5. The microgrid eigenvalues index (\( EI \)) is the maximum real part of the non-zero eigenvalues. If \( EI \) is a negative value, the microgrid is stable and the algorithm goes to step 4 to analyze the other operating points. Otherwise the algorithm returns to step 2 because at least one eigenvalue has been unstable.

6. The nominator of the \( OF \) is the summation of the reactive power mismatches for all converters multiplied by their reactive power droop coefficients and the denominator is the maximum \( EI \) among all operating points (\( n \) points).

\[
OF = \frac{\sum_{i=1}^{s} \sum_{j=1, j\neq i}^{s} |n_i \cdot Q_i - n_j \cdot Q_j|}{|EI_{max}|} \quad (3.19)
\]

7. If the number of iteration reaches its predefined value, the algorithm is terminated, otherwise the next iteration is started.

8. If the voltage limits are violated, the algorithm returns to step 1 and lowers the upper bounds of virtual impedances and virtual inductances to decrease the voltage losses. However, the voltage drops could be compensated by changing the voltage set-points of converters around 1 ± 0.05 p.u..

9. The algorithm reports the optimal virtual inductances and resistances.

### 3.2 ANFIS-based droop control of converters

An optimal virtual impedance at a certain operating point might not be an optimal candidate in another operating point. Moreover, since the voltage drop on virtual resistance has been considerable in previous research, it is proposed to apply pure virtual inductance. The idea is to train an ANFIS network for virtual inductance using a database of possible load levels
3.2.1 The control block diagram

The proposed control block diagram of a converter in island microgrid is demonstrated in Fig.3.4. All blocks in this figure have been explained in Section 3.1 except the ANFIS network which will be designed in this section.

3.2.2 The objective function

The worst damping ratio of microgrid is the minimum damping ratio among all operating points defined by (3.20).

\[ \zeta_{\text{min}}^i = \text{minimum}\{\zeta_1, \zeta_2, \ldots, \zeta_m\} \text{ at operating point } i \]  \hspace{1cm} (3.20)

Considering all \( n \) operating points of the microgrid and their minimum damping ratio (3.20), the total minimum damping of the microgrid is defined by (3.21).

\[ \zeta_{\text{min}} = \text{minimum}\{\zeta_{\text{min}}^1, \zeta_{\text{min}}^2, \ldots, \zeta_{\text{min}}^n\} \]  \hspace{1cm} (3.21)
The summation of the reactive power mismatches among $s$ converters is calculated by (3.22).

$$\Delta Q = \sum_{t=1}^{s-1} |n_{q,t}Q_t - n_{q,t+1}Q_{t+1}|$$

(3.22)

The proposed OF aims at minimizing the reactive power mismatches and enhancing the small-signal stability of microgrid. The arbitrary weighting coefficient ($\beta$) is considered to determine the share of any agent in (3.23).

$$\text{OF} = \beta \Delta Q + (1 - \beta)(1 - \xi_{min})$$

(3.23)

### 3.2.3 The training of ANFIS networks

A three-bus test microgrid is considered for training of ANFIS networks. Full specifications of this microgrid are explained in Publication V. The load is changed by 0.05 p.u. in any step and 140 load scenarios are defined according to Fig.3.5. The optimal virtual inductance and corresponding active and reactive power of converters are saved in all scenarios (Step 6 in Fig.3.6). The ANFIS training is performed using these 140 sets of data by the proposed algorithm of Fig.3.6 as follows.

- **Step 1**: The PSO algorithm is initiated by entering the number of iterations ($Iter$), the inertia weight ($w$), number of population ($nPop$), number
Figure 3.5. The load change scenarios used for ANFIS networks training.

Figure 3.6. The training of ANFIS networks for virtual inductances in island microgrid.

of variables ($nVar$), positive constants ($f_1, f_2$), weighting coefficient ($\beta$), and permissible intervals for variables.

• **Step 2:** The microgrid data including load scenarios and controller
Optimization approaches for droop-based microgrids

parameters are entered.

• **Step 3:** The PSO algorithm is run, while the $OF$ (3.23) is applied. The virtual inductances are playing the roles of particles in PSO, as it is seen in (3.24).

$$y = [L_{v1}, \ldots, L_{vs}]$$ (3.24)

The PSO particles in any iteration are updated by (3.25) where the velocity of this transition is calculated by (3.26).

$$y^{(k+1)}_i = y^{(k)}_i + V^{(k+1)}_i$$ (3.25)

where $y^{(k+1)}_i$, $y^{(k)}_i$, and $V^{(k+1)}_i$ are the location of $i^{th}$ particle in iteration $k+1$, the location of $i^{th}$ particle in iteration $k$, and the velocity of $i^{th}$ particle in iteration $k+1$, respectively.

$$V^{(k+1)}_i = w.V^{(k)}_i + r_1.f_1(MOF^k_i - y^{(k)}_i) + r_2.f_2(MOF_{best}^k - y^{(k)}_i)$$ (3.26)

where $MOF^k_i$ is the minimum value of $OF$ (3.23) for $i^{th}$ particle in $k^{th}$ iteration and $MOF_{best}^k$ is the minimum value of $OF$ experienced by all population in $k^{th}$ iteration. The parameters $w$, $f_1$, and $f_2$ are inertia weight, personal learning coefficient and global learning coefficient, respectively. The coefficients $r_1$ and $r_2$ are drawn by `rand` command in MATLAB ($0 < r_1, r_2 < 1$).

The particles locations are limited by minimum $(y_{i,min})$ and maximum $(y_{i,max})$ permissible values as explained in Equation (3.27).

$$y^{(k)}_i = min\{max(y^{(k)}_i, y_{i,min}), y_{i,max}\}$$ (3.27)

• **Step 4:** The microgrid load-flow is run and depending on the time-step, several operating points are drawn for the microgrid.

• **Step 5:** The eigenvalues analysis for all operating points is accomplished and the eigenvalue with minimum damping ratio is determined. If any of the eigenvalues has a positive real part, that PSO solution is not feasible and therefore is removed.

• **Step 6:** The optimal data set for any converter in the microgrid includes its active power, reactive power, and optimal virtual inductance. The optimal data set including output active power of converters, reactive power of converters, and corresponding optimal virtual inductances of...
Optimization approaches for droop-based microgrids

converters are saved in a matrix \([DM]_{140 \times 3s}\), where \(s\) is the number of converters in the microgrid.

\[
DM = \begin{bmatrix}
P^1_1 & Q^1_1 & L^1_{e1} & \cdots & P^1_s & Q^1_s & L^1_{eS} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
P^{140}_1 & Q^{140}_1 & L^{140}_{e1} & \cdots & P^{140}_s & Q^{140}_s & L^{140}_{eS}
\end{bmatrix}_{140 \times 3s}
\] (3.28)

• **Step 7:** The load scenarios which are seen in Fig.3.5 are run and 140 set of optimal data-sets are prepared. For instance, in scenario 1 the load at bus 1 is 1 p.u. \((R_{load} = 50 \ \Omega \text{ and } L_{load} = 50 \ mH)\) and the loads at bus 2 and 3 are 0 kW. Subsequently, in scenario 2 the load at bus 1 is \(R_{load} = \begin{bmatrix} 50 \\ 0.95 \end{bmatrix} \ \Omega \text{ and } L_{load} = \begin{bmatrix} 0.05 \\ 0.95 \end{bmatrix} \ H\) and the loads at buses 2 and 3 are 0 kW and 0 kVAR. If all 140 data sets are prepared, DM is ready and the algorithm can succeed to step 8, otherwise the next load scenario is run from step 3.

• **Step 8:** The input/output mapping with membership functions (MFs) is performed based on fuzzy rules to generate I/O pairs [15]. The ANFIS training requires a set of training data. The command `anfisedit` in MATLAB environment calls the MATLAB neuro-fuzzy designer as a straightforward tool to train ANFIS controllers. In order to train two-input one-output ANFIS network for \(Lv_1, Lv_2, \ldots, \) and \(Lv_s\), columns 1-3, 4-6,\ldots, and 3s-3 are used as training data, respectively.

• **Step 9:** The trained ANFIS networks are installed in converter control block-diagram of Fig.3.4.
4. Optimization approaches for VSG-based microgrids

The PSO-augmented VSG control aimed at microgrids with static loads (Publication I, Publication VII) and PSO-based VSG control microgrids supplying SIM (Publication IV, Publication VI) are presented in this chapter.

4.1 PSO-based VSG control of microgrids supplying static loads

The control block diagram of a VSG supplying a static load is demonstrated in Fig.4.1. Different blocks have been explained in Section (3.1). The optimization algorithm to extract virtual impedances, $J$ and $D$, is explained in Fig.4.2.

Some blocks such as VSG controller, and voltage controller should be explained here. The explanation of SIM in detail is found in [88].

4.1.1 VSG controller

The VSG control block in Fig.4.1 calculates the frequency reference ($\omega^*$) in terms of measured PLL frequency ($\omega_{PLL}$), nominal frequency ($\omega_n$), active power ($P$), reference active power ($P_0$), droop coefficient ($K_f$), $J$, and $D$.

$$\dot{\omega}^* = -(D/J)(\omega^* - \omega_n) + (P_0 - P)/(J \omega_n)$$
$$-(\omega_{PLL} - \omega_n)(K_f/J)$$

4.1.2 Voltage controller

The $dq$-frame current references are calculated by voltage controller as it is seen in Equations (4.2) and (4.3). The parameters $F$, $\phi_d$, and $\phi_q$ are current state feedback factor, auxiliary variable in d-axis, and auxiliary variable in q-axis, respectively.

$$\dot{\phi}_d = \omega_{PLL} - \omega^* \Rightarrow i_{id}^* = k_{iv} \phi_d + k_{pv} \phi_d + F.i_{od}$$
\[ \phi_q = v_{oq}^* - v_{oq} \Rightarrow i_{iq}^* = k_{iv} \cdot \phi_q + k_{pv} \cdot \phi_q + F \cdot i_{oq} \] 

(4.3)

**Figure 4.1.** The PSO-based VSG control supplying static loads.

The flowchart demonstrated in Fig. 4.2 describes different steps of optimization algorithm to draw VSG parameters and virtual impedances as follows (Publication VII).

![Flowchart](image)

**Figure 4.2.** The optimization algorithm to draw J, D, and virtual impedances.
• Step 1: initialization of variables $J_1, D_1, R_1, L_1, ..., J_s, D_s, R_{us}, L_{us}$ inside their corresponding permissible ranges, where $s$ is the number of VSGs in microgrid.

• Step 2: the PSO algorithm is started using initial values of variables in the previous stage. The optimization variables are considered as particles in PSO, as represented by (4.4).

$$y = [J_1, D_1, R_1, L_1, ..., J_s, D_s, R_{us}, L_{us}]$$ (4.4)

The permissible locations of particles are constrained by minimum $(y_{i,min})$ and maximum $(y_{i,max})$ permissible values. This condition can be expressed by (4.5).

$$y_i^{(k)} = \min\{\max(y_i^{(k)}, y_{i,min}), y_{i,max}\}$$ (4.5)

• Step 3: microgrid load-flow at time interval = $[0 \ t]$ is run using the initial values for $J, D$, and virtual impedances.

• Step 4: $g + h$ eigenvalues at operating point $x_i$ and the $\Delta Q$ are calculated. It is assumed that $i = 1$.

• Step 5: if all eigenvalues at operating point $x_i$ are stable, the $\zeta_{min}^i$ and $\Delta Q$ are reported to the data storage (step 6). Otherwise, flag=1 is set and algorithm proceeds to step 7.

• Step 6: the $\zeta_{min}^i$ for all operating points are saved in this data storage and the $\zeta_{min}$ is chosen as the minimum value among them. The corresponding $\Delta Q$ is also saved in this data storage.

The microgrid at any operating point has $g$ dominant eigenvalues and $h$ non-dominant eigenvalues as seen in (4.6). The minimum damping ratio among dominant eigenvalues at operating point $i$ is named as $\zeta_{min}^i$ as seen in (4.7).

$$\Lambda = \{\lambda_{d1}^d, \lambda_{d2}^d, ..., \lambda_{dg}^d, \lambda_{nd1}^d, \lambda_{nd2}^d, ..., \lambda_{ndh}^d\}$$ (4.6)

The more the damping ratio of the weakest dominant eigenvalue of MG, the less the percentage overshoot of system response.

$$\zeta_{min}^i = \min\{\zeta_1^d, \zeta_2^d, ..., \zeta_g^d\} \text{ at operating point } i$$ (4.7)

where the dominant eigenvalues are those which have small real-parts and the damping of the microgrid is prominently determined by these
eigenvalues. Since there is not a strict definition for dominant eigenvalues, the eigenvalues with real part in a certain interval ($-300 < \text{Real}(\zeta^d) < 0$) are considered as dominant eigenvalues [3],[5]. Considering all $m$ operating points of the microgrid, the total minimum damping of the microgrid is defined by (4.8).

$$\zeta_{\text{min}} = \text{minimum}(\zeta_{\text{min}}^1, \zeta_{\text{min}}^2, \ldots, \zeta_{\text{min}}^m)$$ (4.8)

- Step 7: the $OF$ is calculated considering the data available in step 6 and also the flag received from step 5. If the flag is 1 the PSO removes this unstable solution by considering a large value for $OF$.

$$OF = \Delta Q(p.u.)(1 - \zeta_{\text{min}})$$

$$0 < \zeta_{\text{min}} < 1$$ (4.9)

$$0.95 \text{ p.u.} < v_{oq,1}, v_{oq,2}, \ldots, v_{oq,s} < 1.05 \text{ p.u.}$$

- Step 8: if all the operating points have been analyzed, the algorithm proceeds to step 9, otherwise the next operating point is analyzed starting from step 4.

- Step 9: checking the convergence criterion which can be the value of $OF$ or the number of iterations ($it$). If the algorithm is not converged, the next iteration will begin ($it = it + 1$) from step 2.

- Step 10: the optimal values for $J$, $D$ and virtual impedances are exported by the algorithm and these values are applied to the VSG controllers.

### 4.2 PSO-based VSG control of microgrids supplying SIM

The modeling and control of VSG, its synchronization with grid, and its application to control the voltage and frequency of microgrid have been explained in (Publication I), while the optimization of VSG parameters in an island microgrid including SIM loads has been proposed in (Publication VI). The control block diagram of a VSG supplying static and SIM loads is demonstrated in Fig.4.3.

#### 4.2.1 Optimization algorithm to draw the optimal parameters

The optimization algorithm shown in Fig.4.4 has been proposed in (Publication VI) to calculate the optimal values of virtual impedances, $J$, $D$, and current state-feedback factor ($F$).
Figure 4.3. The control block diagram of VSG in island microgrid including SIM.

Figure 4.4. The optimization algorithm to draw optimal $J$, $D$, virtual impedances and $F$.

- **Start:**
  The PSO particles in a microgrid including $VSG_1$, ..., $VSG_s$ are initialized as follows.

$$y_0 = [J_1, D_1, F_1, R_{V1}, L_{V1}, ..., J_s, D_s, F_s, R_{V8}, L_{V8}] \quad (4.10)$$
• **Input PSO parameters:**
The parameters of PSO algorithm are specified.

• **Load flow calculations:**
The microgrid load flow is run in MATLAB and several operating points are generated ($n$ points).

• **Eigenvalues analysis:**
The eigenvalues of the microgrid at all operating points are calculated by $eig(A_{MG})$ command in MATLAB.

• **Stability constraints:**
If any of the operating points is unstable this solution is removed by PSO.

• **Data saving:**
The stable solutions with corresponding values of $\zeta_{min}$ according to Equation (4.8), reactive power mismatches (4.11), frequency Nadir (4.12), and microgrid stability index (4.13) are saved.

\[ \Delta Q = \sum_{t=1}^{s-1} |n_{q,t}Q_t - n_{q,t+1}Q_{t+1}| \]  
\[ (4.11) \]

The per unit frequency Nadir is calculated by (4.12).
\[ Nadir = |\frac{\omega_{min} - \omega_n}{\omega_n}| \]  
\[ (4.12) \]

It should be noted that, minimizing SI leads to a better damping ratio for the critical eigenvalue.
\[ SI = 1 - \zeta_{min} \]  
\[ (0 < \zeta_{min} < 1) \]  
\[ (4.13) \]

• **Objective function**
Herein; considering the previous definitions for microgrid stability index, the reactive power mismatches, and the frequency Nadir, the proposed $OF$ is calculated by (4.14) for all solutions.
\[ OF = p_1 SI + p_2 \Delta Q + p_3 Nadir \]  
\[ (4.14) \]

where the weighting coefficients $0 < p_1, p_2, p_3 < 1$ are assigned based on the priorities of the microgrid.

• **Updating $MOF_{best}^k$ and $MOF_i^k$:**
The lowest values of $OF$ experienced by any particle in $k^{th}$ iteration ($MOF_i^k$) and by the whole population ($MOF_{best}^k$) are found among all solutions.
• **Updating velocities and particles:**
  The locations of PSO particles are updated based on (4.15) where the velocity of this movement is calculated by (4.16).

\[
y^{(k+1)}_i = y^k_i + V^{(k+1)}_i
\]

(4.15)

where \(y^{(k+1)}_i\), \(y^k_i\), and \(V^{(k+1)}_i\) are the location of \(i^{th}\) particle in iteration \(k+1\), the location of \(i^{th}\) particle in iteration \(k\), and the velocity of \(i^{th}\) particle in iteration \(k+1\), respectively.

\[
V^{(k+1)}_i = w.V^k_i + r_1.f_1(MOF^k_i - y^k_i) + r_2.f_2(MOF^{best}_i - y^k_i)
\]

(4.16)

where \(MOF^k_i\) is the minimum value of \(OF\) (4.14) for \(i^{th}\) particle in \(k^{th}\) iteration and \(MOF^{best}_i\) is the minimum value of \(OF\) experienced by all population in \(k^{th}\) iteration. The parameters \(w\), \(f_1\), and \(f_2\) are inertia weight, personal learning coefficient and global learning coefficient, respectively. The coefficients \(r_1\) and \(r_2\) are drawn by rand command in MATLAB \((0<r_1,r_2<1)\).

• **Variables constraints:**
  The lower and upper bounds for any optimization variable \((J_1, D_1, F_1, ..., J_s, D_s, F_s)\) are determined based on the eigenvalues analysis and permissible voltage drops. These values are shown by two matrices \([\text{VarMin}]_{1\times3s}, [\text{VarMax}]_{1\times3s}\).

• **Limiting to boundaries:**
  If the value of any variable exceeds its permissible interval, its value is limited to the corresponding boundary.

• **Velocity limitation:**
  An upper and lower bound are defined for the particles velocities in terms of their location boundaries (4.17).

\[
V_{i,\text{max}} = \alpha.(y_{i,\text{max}} - y_{i,\text{min}})
\]

\[
V_{i,\text{min}} = -\alpha.(y_{i,\text{max}} - y_{i,\text{min}})
\]

(4.17)

• **Velocity adjustment:**
  The velocity of particles are limited to upper and lower bounds by (4.18).

\[
V^{(k)}_i = \min\{\max\{V^{(k)}_i, V_{i,\text{min}}\}, V_{i,\text{max}}\}
\]

(4.18)

• **Convergence criteria:**
  The algorithm is run for a specific number of iterations. If the last iteration has been run, the algorithm is assumed to be converged.
End:
A set of optimized values \((F_1, J_1, D_1, R_{V1}, L_{V1}, ..., F_s, J_s, D_s, R_{VS}, L_{VS})\) are exported.
5. Results and Discussion

This chapter provides an overview of the simulation results drawn in Publications I-VII. The obtained results are simply categorized into two sections (5.1 and 5.2) corresponding with the previous chapters 3 and 4.

5.1 Optimization approaches for droop-based microgrids

5.1.1 PSO-based droop control of converters

A 2-bus test microgrid is modeled and analyzed in Publication III. The parameters of this microgrid are listed in Table (5.1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_f, C_f$</td>
<td>4.2 mH, 15 μF</td>
<td>$r_f, r_n$</td>
<td>0.5 Ω, 1000 Ω</td>
</tr>
<tr>
<td>$R_d, f_{sw}, u_{dc}$</td>
<td>2.025 Ω, 10 kHz, 150 V</td>
<td>$k_{p,PLL}, k_{i,PLL}$</td>
<td>0.25, 2</td>
</tr>
<tr>
<td>$r_c, \omega_c$</td>
<td>0.09 Ω, 50.26 rad/s</td>
<td>$L_c, \omega_{PLL}$</td>
<td>0.5 mH, 7853.98 rad/s</td>
</tr>
<tr>
<td>$V_{eqN}, \omega_n$</td>
<td>85 V, 377 rad/s</td>
<td>$m, n$</td>
<td>0.001, 0.001</td>
</tr>
<tr>
<td>$R_{load1}, L_{load1}$</td>
<td>25 Ω, 15 mH</td>
<td>$R_{load2}, L_{load2}$</td>
<td>25 Ω, 7.5 mH</td>
</tr>
<tr>
<td>$R_{line}, L_{line}$</td>
<td>0.15 Ω, 0.4 mH</td>
<td>$R_{pert}, L_{pert}$</td>
<td>25 Ω, 0.1 mH</td>
</tr>
<tr>
<td>$k_{pv}, k_{iv}$</td>
<td>0.5, 25</td>
<td>$k_{pc}, k_{ic}$</td>
<td>1, 100</td>
</tr>
</tbody>
</table>

The current state-feedback factor ($F$) is changed and the major eigenvalues of the microgrid are drawn, simultaneously. Fig.5.1 shows the eigenvalues of the test microgrid while $F$ is changing from zero to infinity. The dominant eigenvalues are demonstrated in Fig.5.1a and the critical eigenvalues are plotted in Fig.5.1b. It is noteworthy that those values of $F$ which cause the microgrid to become unstable are the boundary of instability. According to the figure, for a specific interval ($0 < F < 0.53$) increasing this factor enhances the microgrid stability by making the real-part of the eigenvalues more negative. In another interval ($0.53 < F < 0.76$), by rising $F$ the microgrid stability has deteriorated. The optimal value of $F$ from
stability point of view is 0.53 which leads to better damping of response.

![Graph showing all dominant eigenvalues](image1)

**Figure 5.1.** All dominant eigenvalues

![Graph showing critical eigenvalues](image2)

**Figure 5.2.** Critical eigenvalues

Fig. 5.2 depicts the reference frequency of microgrid under study in three different cases \( F = 0, 0.53, \) and \( 0.76 \). In the third case with \( F = 0.76 \) which is the boundary of instability, the undamped oscillations in the reference frequency in Fig. 5.2 are visible (light-blue curve). Consequently, a big value of \( F \) could deteriorate the microgrid stability. Comparing the frequency references for \( F = 0 \) and \( 0.76 \) in Fig. 5.2 clarify that the magnitudes of oscillations are almost similar. However, the settling time in second case with \( F = 0.53 \) is smaller than two other cases.

The proposed PSO-based droop control of converters (Section 3.1) introduces an optimization algorithm to calculate optimal values of virtual impedances to correct the reactive power sharing and enhance the small-signal stability of microgrid. The optimization method has been used to calculate the virtual impedances for the 3-bus test microgrid and the optimal virtual impedances have been presented in Table 5.2.

An initial load by 29 kW is installed at bus 1 of 3-bus microgrid and the other buses do not have local loads. At \( t = 2 \) s the 29 kW load \( (R_{\text{pert}2} = 5 \, \Omega, X_{\text{pert}2} = 1000 \, \Omega) \) is switched in at bus 1 and different characteristics of the microgrid are analyzed hereafter.

Fig. 5.3 demonstrates the major eigenvalues of the 3-bus microgrid while
Results and Discussion

![Graph showing reference frequencies](image)

**Figure 5.2.** The microgrid reference frequency for three different current state-feedback factors, $F = 0$, $F = 0.53$, and $F = 0.76$.

**Table 5.2.** 3-BUS MICROGRID AND CONVERTERS PARAMETERS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_f, C_f$</td>
<td>1.35 mH, 50 μF</td>
<td>$r_f, r_n$</td>
<td>0.1 Ω, 1000 Ω</td>
</tr>
<tr>
<td>$R_{d, fsw, u_{dc}}$</td>
<td>5 Ω, 6 kHz, 650 v</td>
<td>$k_{p, PLL}, k_{i, PLL}$</td>
<td>0.25, 2</td>
</tr>
<tr>
<td>$r_c, \omega_c$</td>
<td>0.03 Ω, 70 rad/s</td>
<td>$L_c, \omega_{c, PLL}$</td>
<td>0.35 mH, 7853.98 rad/s</td>
</tr>
<tr>
<td>$V_{ogN}, \omega_n$</td>
<td>380 V, 314 rad/s</td>
<td>$m, n$</td>
<td>0.000094, 0.0013</td>
</tr>
<tr>
<td>$R_{load1}, L_{load1}$</td>
<td>25 Ω, 15 mH</td>
<td>$R_{load2}, L_{load2}$</td>
<td>25 Ω, 7.5 mH</td>
</tr>
<tr>
<td>$R_{line1}, X_{line1}$</td>
<td>0.23 Ω, 0.1 Ω</td>
<td>$R_{line2}, X_{line2}$</td>
<td>0.35 Ω, 0.58 Ω</td>
</tr>
<tr>
<td>$R_{pert2}, L_{pert2}$</td>
<td>5 Ω, 0.1 mH</td>
<td>$R_{c1}, L_{c1}$</td>
<td>0.852 Ω, 0.036 H</td>
</tr>
<tr>
<td>$R_{v2}, L_{v2}$</td>
<td>0.561 Ω, 0.024 H</td>
<td>$R_{v3}, L_{v3}$</td>
<td>0.335, 0.018 H</td>
</tr>
<tr>
<td>$k_{pv}, k_{iv}$</td>
<td>1, 45</td>
<td>$k_{pc}, k_{ic}$</td>
<td>10.5, 1600</td>
</tr>
</tbody>
</table>

applying the proposed algorithm and installing the virtual impedances of Table 5.2 in the microgrid and also the case without these virtual impedances [5]. It is seen that the minimum damping is related to mode 25, 26 which is 25.528% and most of the other damping modes are damped perfectly and have the damping ratio of 100%. It is seen that the microgrid eigenvalues index (EI) before installing optimal virtual impedances is $EI = 0.311$ and the microgrid EI after applying the proposed virtual impedances is $EI_v = 2.01$. The proposed virtual impedances could apparently enhance the microgrid’s EI.

The frequency of converters in 3-bus microgrid while applying optimal virtual impedances and using the control method in [5] are demonstrated in Fig.5.4. The load change of 29 kW occurs at bus 1 at $t = 2$ s. Fig.5.4 shows that the Nadir while applying the proposed optimal virtual impedances is 49.84 Hz and on the other hand the point of minimum frequency while applying the control method in [5] is 49.71 Hz which demonstrates the enhanced performance of the proposed control and optimal virtual impedances in microgrid frequency control. The RoCoF is also lower while deploying the proposed optimal virtual impedances. The steady state frequency of microgrid while applying the proposed method
Results and Discussion

**Figure 5.3.** Major eigenvalues of the 3-bus microgrid applying the proposed control method (black squares) and the method in [5] (red diamonds).

and the method in [5] are 49.87 Hz and 49.85 Hz, respectively which are roughly equal.

**Figure 5.4.** The comparison of 3-bus microgrid frequencies applying the proposed control strategy (full lines) and the method in [5] (dashed lines).

The power injected by converters to the microgrid in two separate cases; applying optimal virtual impedances and using the method in [5] are demonstrated in Fig.5.5. The $P_{1\text{new}}$ which is the active power injected by converter 1 (red line in the top of Fig.5.5) in load change scenario has a lower overshoot than the case which uses the method in [5] (red dashed line in the top of Fig.5.5). In the steady-state, any converter injects 9.74 kW while applying the proposed optimal virtual impedances while any converter injects 9.74 kW in case the method in [5] is applied. The differences in the steady-state injected powers are negligible. However, the reactive powers injected by three converters while applying the proposed optimal virtual impedances are roughly 285 VAr which is consumed in transmission lines. In case the method in [5] is used the reactive powers for converters 1 to 3 are 5.132 kVAR, -1.292 kVAR, -3.135 kVAR, respectively. The proposed optimal virtual impedances could successfully remove the reactive power exchanges among converters and facilitates the fair reactive power sharing.

The output current components of three converters are depicted in Fig.5.6 while the proposed optimal virtual impedances are installed ($i_{od\text{ new}}$) and
in case the method of [5] is deployed \((i_{od} \text{ in [5]})\). The q-axis current components of converters while deploying the optimal virtual impedances demonstrate a lower overshoot (maximum overshoot = 38.9 A) than the case with control method in [5] (maximum overshoot = 50.88 A) which is a significant advantage of the proposed control method. The d-axis current components while installing the optimal virtual impedances are depicted in the top part of Fig.5.6. It is visible that the q-axis output currents while applying the optimal virtual impedances reach at identical values (0.763 A). However the converters 1-3 generate different q-axis currents 3.349 A, -2.553 A and -8.12 A while applying the method in [5]. The proposed optimal virtual impedances successfully remove the q-component current exchanges among converters.

The output voltage components of three converters in 3-bus microgrid are depicted in Fig.5.7. The d-axis voltage component \((v_{od})\) either using the proposed method or the method in [5] have a zero steady state value. The q-axis voltage components while installing the optimal virtual impedances start from 400 V and after the 29 kW load change at \(t = 2 \text{ s}\) reach 367.9 V, 379 V, 387.4 V for converters 1 to 3, respectively. The voltages after the load change have roughly less than 3 % voltage drop which is acceptable. The point is that the reference voltage was 1.05 p.u. to compensate the
Results and Discussion

Figure 5.6. Converters output currents in 3-bus microgrid applying the proposed control strategy (full lines) and the method in [5] (dashed lines).

voltage drops on virtual impedances. The q-axis voltage components while applying the method in [5] are shown as dashed lines in the bottom part of Fig.5.7. The \( v_{oq1}, v_{oq2}, v_{oq3} \) while deploying the method in [13] start from 380 V and reach at 374.3 V, 382.3 V, 385.1 V after load change at \( t = 2 \) s, respectively. Both control methods keep the voltage in a permitted interval after the load-change scenario.

5.1.2 ANFIS-based droop control of converters

A 3-bus test microgrid is implemented as seen in Fig.5.8. Details of the microgrid (except the loads) are found in Table.5.2. The microgrid has initially no load. Firstly, the sensitivity of reactive power mismatches and the damping of worst eigenvalue with respect to \( \beta \) are scrutinized. Then the ANFIS networks are trained by the proposed algorithm and using ANFIS toolbox in MATLAB. Finally the load change scenario is implemented and the dynamic characteristics of the microgrid are evaluated.

The loads at buses 1 and 3 are \( R_{pert} = 25 \) Ω and there is no load at bus 2. The weighting coefficient (\( \alpha \)) in the \( OF (3.23) \) affects the share of any participant. The value of \( \beta \) is changed from 0 to 1 and the optimal values of optimal virtual inductances are determined by steps 1-7 of the proposed algorithm (Fig.3.6). The bigger values of \( \beta \) lead to lower reactive
Results and Discussion

![Converter output voltages in 3-bus microgrid applying the proposed control strategy (full lines) and the method in [5] (dashed lines).](image)

**Figure 5.7.** Converters output voltages in 3-bus microgrid applying the proposed control strategy (full lines) and the method in [5] (dashed lines).

![The 3-bus test microgrid.](image)

**Figure 5.8.** The 3-bus test microgrid.

power mismatches and lower values of $\beta$ enhance the stability of microgrid by enhancing the minimum damping ratio of eigenvalues. As Fig. 5.9a demonstrates, the maximum reactive power mismatch is seen at $\beta = 0$. By increasing $\beta$ the reactive power mismatches decreases. It should be noted that for $\beta > 0.5$ the rate of drop in reactive power mismatch is negligible.

On the other hand, the minimum damping ratio of the eigenvalues is shown in Fig. 5.9b for different values of $\beta$. It is seen that for $\beta = 0$ the minimum damping ratio of eigenvalues is 37.62% which is the maximum possible value. By increasing $\beta$, the minimum damping ratio of eigenvalues decreases gradually. The rate of reducing the damping ratio for $\beta > 0.5$ is negligible.

Consequently, choosing $\beta = 0.5$ is a good compromise for the multi objective equation (3.23) to have a relatively low reactive power mismatch and a high minimum damping ratio.
Results and Discussion

Figure 5.9. The sensitivity analysis for reactive power mismatches and the minimum damping ratio of eigenvalues with respect to weighting factor ($\beta$).

Three ANFIS networks are required in the control block-diagram. A two-input one-output ANFIS network is trained for any converter by anfisedit command in MATLAB. The full specifications of ANFIS networks are listed in Table 5.3. The active power and the reactive powers are inputs and virtual inductance is the output which are placed in first, second, and third column of a matrix, respectively. The data sets include 140 load scenarios. The ANFIS network for $L_{v1}$, $L_{v2}$, $L_{v3}$ are depicted in Fig.5.10. The virtual inductance $L_{v1}$ in Fig.5.10a shows two opposite trends around $P_1 = 4583.1$ W, before and after this point the virtual inductance value shows a drop and a growth by a rise in active power, respectively.

The ANFIS network for $L_{v2}$ in Fig.5.10b demonstrates roughly a direct relationship between the value of $P_2$ and the value of $L_{v2}$. However, the plain slope in $Q_2 - L_{v2}$ axis has a breaking point ($Q_2 = 975.36$ VAR). Before and after this point the slopes have positive and negative values.

The ANFIS network of converter 3 is also depicted in Fig.5.10c. The maximum values of $L_{v3}$ are devoted to the minimum active and reactive power injections. There is a breaking point in $P_3 - L_{v3}$ axis so as the rate of change of $P_3$ before and after $P_3 = 4561.45$ W are total different. For active power lower than this value, the change of virtual inertia is independent from change in active power of converter 3. However, the points over this value present a dramatic change in $L_{v3}$ by changing $P_3$.

Table 5.3. ANFIS NETWORKS PARAMETERS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or Type</th>
<th>Parameter</th>
<th>Value or Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of MFs</td>
<td>3,3</td>
<td>MF type</td>
<td>trimf, constant</td>
</tr>
<tr>
<td>Epochs</td>
<td>50</td>
<td>Error tel.</td>
<td>0.0001</td>
</tr>
<tr>
<td>FIS training</td>
<td>Grid partition</td>
<td>Optim. Method</td>
<td>hybrid</td>
</tr>
</tbody>
</table>
Results and Discussion

Figure 5.10. The trained ANFIS networks for virtual inductances a) $L_v1$, b) $L_v2$, c) $L_v3$

Load changes scenario

A static load $(R_{pert}+jX_{pert})$ is connected to bus 1 at $t=0.5$ s, then the same load is switched in at bus 2 at $t=1.5$ s, and finally this load is connected to bus 3 at $t=2.5$ s. Different dynamic characteristics of the microgrid; obtained by the proposed method and the control method in [5], are demonstrated and compared.

The frequency of the microgrid in different buses is shown in Fig.5.11 using the proposed control method and also the control method in [5]. The frequency fluctuations while applying the proposed control method are negligible in comparison with applying the control method in [5]. The microgrid frequency nadir values are shown in Fig.5.11 at maximum deviation points. The frequency Nadir while applying ANFIS-based control method is 49.9529 Hz and the corresponding value while applying the control method in [5] is 49.9435 Hz.

The $dq$ voltage components are demonstrated in Fig.5.12 while applying the proposed ANFIS-based control method and the control method in [5]. The d-axis voltage components are changing around zero in Fig.5.12a, either using the ANFIS-based control method or applying the control method
Results and Discussion

Figure 5.11. The microgrid frequency in load change scenario while applying the proposed ANFIS controller and the control method in [5].

Figure 5.12. The microgrid voltage components for converters 1, 2, 3 in load change scenario while applying the proposed ANFIS controllers and the controller in [5].

The current components injected by converters 1, 2, and 3 are demonstrated in Fig.5.13. The d-axis currents in Fig.5.13a by ANFIS-based control method show lower mismatches and fluctuations than d-axis cur-
rents drawn by [5]. The maximum current mismatches in Fig. 5.13a using the proposed ANFIS-based control and using the control method in [5] are 0.37 A and 2.37 A, respectively. Therefore, the ANFIS-based method excels the control method of [5] in minimizing the d-axis current mismatch. The steady-state values of q-axis current components in Fig. 5.13b are identical, but the current overshoot and fluctuations while applying the ANFIS-based control method are lower than the corresponding values while applying the control method in [5] (3.2381 A and 3.2595 A, respectively). Consequently, the performance of the ANFIS-based control method exceeds the performance of the control method in [5] from the current point of view.

![Graph showing current components](image)

**Figure 5.13.** The current components for converters 1, 2, 3 in load change scenario applying the proposed ANFIS controllers and the controllers in [5].

The active powers injected by converters 1, 2, and 3 are shown in Fig. 5.14a. The steady-state active power values using both methods are 1.74 kW, 3.18 kW, and 4.57 kW at t= 1.5, 2.5, and 3.5 s, respectively. The maximum overshoot in active power curves by the proposed ANFIS-based controller is 0.96 kW and the corresponding value by the control method in [5] is 1.36 kW in Fig. 5.14a. Consequently, the active power overshoot is decreased by the proposed ANFIS-based control method which is a prominent advantage. The reactive powers injected by converters 1, 2, and 3 are shown in Fig. 5.14b. The maximum reactive power mismatches while applying the ANFIS-based controller and the control method in [5] are 0.277 kVAr and 2.74 kVAr, respectively. Therefore the reactive power mismatches are decreased substantially which is a major contribution of the
Results and Discussion

![Graph showing active and reactive powers](image)

**Figure 5.14.** The converters active and reactive powers in load change scenario applying the proposed optimal parameters and the corresponding voltage components in [5], a) active power ($P$), b) reactive power ($Q$).

The proposed ANFIS-based controller. It should be noted that the ANFIS-based controllers are independent of the load-change location in the microgrid and they can successfully cope with the load changes in three buses at $t=0.5$ s, $t=1.5$ s, and $t=2.5$ s.

5.2 Optimization approaches for VSG-based microgrids

5.2.1 PSO-based VSG control of microgrids supplying static loads

The proposed method has been introduced in Section 4.1 and it is implemented on a 3-bus test microgrid to evaluate its performance. Full specifications of 3-bus test microgrid is found in Table 4.2 in (Publication VII). The load $R_{load3}+jX_{load3}$ is switched in at $t=1$ s and $R_{load1}+jX_{load1}$ is switched in at $t=3$ s. Different characteristics of the test microgrid following this load-change scenario are analyzed herein. The performance of the proposed method is compared with the basic VSG method which has been proposed in [10].

The eigenvalues of the 3-bus microgrid are depicted in Fig.5.15. The whole eigenvalues in Fig.5.15a locate in left half plain (except one in (0,0)).
Therefore, the microgrid is asymptotically stable while it is controlled by conventional control method (“VSG”) or the proposed optimization method (“VSG + VI”). Focusing on eigenvalues in Fig.5.15b discloses that the weakest dominant eigenvalue while using “VSG + VI” method has a better damping ratio and overall stability. For instance, the dominant eigenvalue $\lambda_{\min,1}^d$ while using “VSG” control is $-4.83 \pm 8.17$, however, the dominant eigenvalue $\lambda_{\min,2}^d$ while applying “VSG + VI” is $-7.25 \pm 11.69$. Consequently, the damping ratio is enhanced from 50.87% to 52.70% using the “VSG + VI” control method. The non-dominant stable eigenvalues have minor effects on the MG small-signal stability and can be ignored.

![Eigenvalues of 3-bus microgrid](image)

**Figure 5.15.** The eigenvalues of 3-bus microgrid, a) all eigenvalues, b) dominant eigenvalues.

The bar diagram in Fig.5.16 demonstrates the damping ratios ($\zeta$) for all MG eigenvalues. The minimum damping ratio while applying “VSG” control and “VSG + VI” control are 50.87% and 52.70%, respectively. Therefore, the proposed “VSG + VI” control enhance the damping ratio of the weakest dominant eigenvalue.

The output $dq$ voltage components of VSGs are seen in Fig.5.17. The $d$-axis voltages are forced to zero in both control methods and Fig.5.17a verifies that either using “VSG” or “VSG + VI” the $d$-axis voltages are zero, as expected.
The \( q \)-axis voltages while using “VSG” or “VSG + VI” method should satisfy the voltage drop constraint (4.9). As it is seen in Fig.5.17b, the steady-state voltage drops while using “VSG” and “VSG + VI” methods are 1.36 V and 3.20 V, respectively. In other words, the \( q \)-axis output voltages while applying “VSG + VI” method and “VSG” method are 0.97 p.u. and 0.99 p.u.. However, the voltage drops while applying “VSG + VI” method is more than the voltage drops using “VSG” method, but still the percentage of voltage drops in both methods are acceptable. These voltage drops can be corrected in secondary voltage control by changing the voltage set-points.

The current components of three VSGs in \( dq \) reference frame are depicted in Fig.5.18. The \( d \)-axis currents are shown in Fig.5.18a. The maximum \( d \)-axis current overshoots while using “VSG” control and “VSG + VI” control are 2 A and 0.84 A, respectively. On the other hand, the \( d \)-axis current mismatches among VSGs are 2.46 A and 0.36 A while using “VSG” and “VSG + VI”, respectively. The lower current overshoot and current mismatches in \( d \)-axis are prominent advantages for proposed “VSG + VI” method.

The \( q \)-axis current components are demonstrated in Fig.5.18b in load change scenario. The steady-state \( q \)-axis currents while using “VSG” or “VSG + VI” method have identical values. However, the settling time while applying “VSG + VI” method is clearly shorter than the case with “VSG” control. For example, the VSG response is settled at \( t = 5 \) s and \( t = 4 \) s while applying “VSG” control and “VSG + VI” control, respectively. Therefore the “VSG + VI” response is faster than “VSG” response. Moreover, the maximum \( q \)-axis current overshoot while applying “VSG” and “VSG + VI” are 8.32 A and 7.74 A, respectively.

Altogether, the faster current response with lower overshoot and smaller current mismatches are the major advantages of “VSG + VI” method in comparison with “VSG” control.
Fig. 5.19 depicts the active and reactive powers injected by VSGs to the 3-bus microgrid. The maximum active power injected by VSG 1 to the microgrid in Fig. 5.19a while applying “VSG” and “VSG + VI” control are 4665 W and 4230 W, respectively. Therefore lower active power overshoot is an advantage of “VSG + VI” method.

Moreover, the settling time of active power while applying “VSG + VI” method is shorter in Fig. 5.19a. For instance, the $P_1$ is settled at $t = 5$ s and $t = 4$ s while applying “VSG” and “VSG + VI”, respectively. Consequently, the active power response is prominently faster while using “VSG + VI” control method.

The reactive powers injected to the 3-bus microgrid are seen in Fig. 5.19b. The maximum reactive power injected to the MG while applying “VSG” and “VSG + VI” control methods are 1059.92 and 548.75 VAR, respectively. On the other hand, the maximum reactive power mismatches while applying “VSG” and “VSG + VI” methods are 1203 and 207.25 VAR, respectively. Therefore, the smaller reactive power mismatch is an outstanding pros for “VSG + VI” method.

All in all, the “VSG + VI” control method excels “VSG” control by having a shorter settling time, smaller power overshoot, and a negligible reactive
Results and Discussion

5.2.2 PSO-based VSG control of microgrids supplying SIM

Feasible Ranges of Microgrid Parameters in Presence of SIM
The value of active power droop coefficient is effective in microgrid small-signal stability analysis. Fig.5.20 demonstrates the major eigenvalues of the test microgrid while the active power droop coefficient is changing from 0 to 1. As it is seen at $m = 0.487$ two branches of eigenvalues enter the right-half plain and consequently the microgrid becomes unstable. The microgrid controller could have any value in between $0 < m < 0.487$ based on the control strategy and the $OF$ of the microgrid.

The reactive power droop coefficient is another significant parameter contributing to the microgrid stability. The dominant eigenvalues of the test microgrid are drawn in Fig.5.21 while the reactive power droop coefficient is changing from 0 to 1. It is seen that the reactive power coefficient could change in a limited interval from 0 to 0.017 to keep the microgrid eigenvalues in left half plain of complex plain which is known to be the asymptotically stable region.

Virtual impedances which are applied to correct the reactive power be-
Figure 5.19. The injected active and reactive powers of VSGs in 3-bus microgrid in load change scenario.

Figure 5.20. The effect of changing active power droop coefficient (from 0 to 1) on microgrid eigenvalues.

behavior of converters while enhancing its stability. The major eigenvalues of microgrid are drawn and depicted in Fig. 5.22 while the virtual inductance of converter 1 and converter 2 are changed from 0 to 1. It is seen that the maximum permissible value for $L_v^1$ and $L_v^2$ are 75 mH and 67 mH, respectively.

The virtual resistances can affect the microgrid small-signal stability as it is seen in Fig. 5.23. Increasing either $R_v^1$ or $R_v^2$ propels the eigenvalues
Results and Discussion

Figure 5.21. The effect of changing the reactive power droop coefficient (n changes from 0 to 1) on microgrid eigenvalues.

(a) Increasing $L_v_1$ from 0 to 1 H.

(b) Increasing $L_v_2$ from 0 to 1 H.

Figure 5.22. The effect of changing virtual inductance of converters on microgrid eigenvalues.

towards the right-half of the complex plain. It is seen that choosing virtual resistances in an interval identical to those corresponding inductances could keep the microgrid stable and the eigenvalues stay in left-half plain while $R_v_1$ or $R_v_2$ is set at a value ranging from 0 to 1.
Results and Discussion

(a) Increasing $R_v1$ from 0 to 1 $\Omega$.

(b) Increasing $R_v2$ from 0 to 1 $\Omega$.

Figure 5.23. The effect of changing virtual resistance of converters on microgrid eigenvalues.

VSG modeling and parameters tuning
A three-bus test microgrid which includes a SIM load and a RL load is simulated in this study. The PSO algorithm parameters, SIM parameters, and VSGs parameters are listed in Tables I-III in Publication VI, respectively. The load change scenario occurs at $t = 2$ s when a 5.8 kW static load ($R_{pert1} + j \omega_n L_{pert1}$) is switched in at bus 1 in parallel with its initial load of $R_{load1} + j X_{load1}$. The bus 2 is in no-load condition. The initial load of bus 3 is also zero and the load torque of $5 \times 11.9$ N.M is enforced to the motor in bus 3 at $t = 4$ s. The optimal parameters drawn by the proposed optimization algorithm (Fig.4.4) and the $OF$ in Publication II are listed in Table 5.4. Hereafter, different dynamic characteristics of the 3-bus microgrid are analyzed.

It is seen in Fig.5.24a that both methods show a similar steady state $d$-axis voltage which is forced to be zero in both control methods. The maximum $d$-axis voltage deviations are -1 V, -1.4, by the proposed method and the one in Publication II, respectively. However, the $q$-axis voltage while applying the proposed control method reaches at 367.30 V at $t = 5$ s in bus 3, while the results drawn from Publication II demonstrate the
Table 5.4. OPTIMAL CONTROLLER PARAMETERS

<table>
<thead>
<tr>
<th>Proposed optimal parameters</th>
<th>Method in Publication II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F, J_v$</td>
<td>0.337, 5.66</td>
</tr>
<tr>
<td>$F, J_v$</td>
<td>0.132, 6.37</td>
</tr>
<tr>
<td>$D, L_{c1}$</td>
<td>294.80, 0.0046</td>
</tr>
<tr>
<td>$D, L_{c1}$</td>
<td>213.71, 0.007</td>
</tr>
<tr>
<td>$L_{c2}, L_{c3}$</td>
<td>0.0035, 0.0074</td>
</tr>
<tr>
<td>$L_{c2}, L_{c3}$</td>
<td>0.00598, 0.00715</td>
</tr>
<tr>
<td>$R_{c1}, R_{c2}$</td>
<td>0.0707, 0.14371</td>
</tr>
<tr>
<td>$R_{c1}, R_{c2}$</td>
<td>0.10065, 0.05793</td>
</tr>
<tr>
<td>$R_{c3}$</td>
<td>0.12455</td>
</tr>
<tr>
<td>$R_{c3}$</td>
<td>0.16430</td>
</tr>
<tr>
<td>$p_1, p_2, p_3$</td>
<td>0.2, 0.6, 0.2</td>
</tr>
</tbody>
</table>

lowest voltage of 365.56 V in bus 3. Consequently, applying the optimal parameters obtained from the proposed optimization algorithm enhanced the voltage by 1.74 V.

![Graph](image1)

(a) d-axis voltage component ($v_{od}$)

![Graph](image2)

(b) q-axis voltage component ($v_{oq}$)

Figure 5.24. The microgrid voltage components for VSGs 1, 2, 3 in load change scenario applying the proposed optimal parameters and the optimal parameters in Publication II.

It is seen in Fig.5.25 that the frequency Nadir using the proposed control method is lower than the corresponding frequency while applying the optimal control parameters drawn from Publication II. The frequency Nadir is enhanced from 49.92 Hz to 49.94 Hz by applying the proposed optimal control parameters in this study.

The dominant eigenvalues of the 3-bus test microgrid are demonstrated in Fig.5.26. The critical eigenvalues (A) have been $-2.92 \pm 17.12$ and $-0.36$
Results and Discussion

Figure 5.25. The microgrid frequency in load change scenario for VSGs 1, 2, and 3 while applying the proposed optimal parameters and the optimal parameters in Publication II.

Figure 5.26. The dominant eigenvalues of microgrid applying the proposed optimal parameters and optimal parameters in Publication II.

± 20.7 while using the proposed optimization method and the optimization method in Publication II, respectively. The corresponding damping ratios of these eigenvalues have been 16.81 % and 1.7 %, respectively. Therefore, the proposed optimization method prominently enhanced the microgrid small-signal stability compared to the method in Publication II. The minimum damping ratio at point B using the proposed method has been 78.05 % and the minimum value by the method in Publication II is 74.33 % and these modes are also better damped using the proposed control method.

The active power supplied by VSGs in two cases in Fig.5.27a present a similar performance either by the proposed optimal parameters or by those optimal parameters drawn from Publication II. After the load-change at t = 2 s any VSG injects 3.09 kW and after t = 4 s injects 6.22 kW.

The VSGs reactive powers at t = 5 s while applying the proposed optimal parameters in Fig.5.27b are 2.54 kVar, 2.62 kVar and 2.91 kVar for VSGs 1-3, respectively. On the other hand, while the optimal parameters drawn from Publication II are applied, the VSGs inject 2.25 kVar, 2.51 kVar, 3.25 kVar at t = 5 s, respectively. Consequently, the reactive power mismatches have been 0.37 kVAR and 1 kVAR while applying the proposed optimal parameters and the optimal parameters in Publication II. Thereupon, the
Results and Discussion

Figure 5.27. The active and reactive powers for VSGs 1, 2, 3 in load change scenario while applying the proposed optimal parameters and the optimal parameters in Publication II.

reactive power mismatches have been declined from 1 kVAr to 0.37 kVAr by the proposed optimization method.
6. Conclusions and outlook

The artificial intelligence-based control methods are novel and ever-growing means in modern power systems with a major penetration of converter-based DGs. The dynamic characteristics of microgrid, such as small-signal stability, voltage drops, frequency Nadir and RoCoF, current overshoot and mismatches, and power overshoot and sharing can be optimized by these control methods. This thesis has made several contributions to the research field of artificial intelligence-based control of microgrids. This chapter summarizes those contributions and suggests prospective research line for future.

6.1 Conclusions

First, a novel control framework for adjusting the frequency and voltage of island microgrid based on the VSG idea and controlling all the DGs in common reference frame is proposed and examined in both island and grid-connected applications. In island operating mode, the voltage and frequency are controlled within their permitted values and RoCoF and Nadir are adjusted by $J$ and $D$. The pre-synchronization process facilitates the smooth grid connection (Publication I).

The thesis developed the small-signal modeling and analysis of an island microgrid including PLL and virtual impedances. Afterwards, a PSO-based optimization method is introduced which calculates the virtual impedances for the converters based on the microgrid small-signal stability analysis and reactive power sharing. It analyzes the small-signal stability in all different operating points to ensure the microgrid small-signal stability. The microgrid voltage and frequencies have been kept within standard limits, the microgrid stability index is enhanced and the reactive power mismatches are minimized using the proposed control method (Publication II). In Publication III, the thesis introduced a small-signal model for an inverter-based microgrid including PLL and current state-feedback ($F$) and examined the effect of $F$ on the microgrid small-signal stability. It clarified
Conclusions and outlook

that there is an optimal value for $F$ regarding the microgrid small-signal stability which leads to better microgrid stability, RoCoF, and dynamic response.

In Publication IV, the thesis introduced a small-signal modeling for an island microgrid including PLL, resistive-inductive loads, SIM, and lines. Moreover, the feasible ranges of droop coefficients, damping resistor, current state-feedback, virtual impedances, and filtering inductances are drawn from the stability point of view.

In Publication V, the thesis proposed a novel control method for a converter-interfaced microgrid including static loads, lines and PLL. Afterwards, it defined an algorithm to train ANFIS networks which are new elements in the proposed control method. These elements determine the virtual inductance values in terms of active and reactive power of converter. The ANFIS-based method applied PSO algorithm to draw optimal training data in all load scenarios. Finally, the training-data is delivered to the ANFIS training unit. Trained networks are installed in the converter controller and a simulation scenario including three successive load changes in the microgrid is implemented. The proposed control method could favorably minimize the reactive power mismatches among converters (independent of the load change location), enhance the dynamic response of converter, and stabilize the eigenvalues of microgrid.

In Publication VI, the thesis models an inverter-interfaced microgrid which supplies static loads and SIM by VSG. Subsequently, a generalized small-signal stability analysis framework is proposed for an islanded microgrid including several VSGs, lines, static loads, and SIM loads. Afterwards, the permissible intervals for VSG parameters are drawn according to the microgrid small-signal stability analysis. These permissible intervals are compared for static and SIM load. Finally, a novel optimization platform is introduced which utilizes the PSO algorithm to draw optimal values for VI, J, D, and F. The proposed optimization platform enhances the microgrid stability, minimizes voltage drops on the buses, the reactive power mismatches, and the frequency Nadir, simultaneously.

In Publication VII, the thesis spotlights on the optimization of VSG parameters and VI in islanded microgrids using PSO. A small-signal model for microgrid is developed and the permissible ranges of $J$ and $D$ based on microgrid small-signal stability are evaluated afterwards. Moreover, VI are considered to decrease the reactive power mismatch between converters. Finally, considering the permitted intervals for these parameters, a novel optimization method and $OF$ are defined to calculate VSG parameters and VI in the islanded microgrid. The proposed optimization method enhances the small-signal stability of the microgrid, decreases the current overshoot and minimizes reactive power mismatches.
6.2 Outlook

Considering the contributions of the thesis and the state of the art, the author introduces the following research topics to pave the way for future studies:

1. Since the dynamics of DC source or converter-side in some RES applications such as wind or PV can affect the small-signal stability of the islanded microgrids and the corresponding optimal values of VSG parameters, the modeling and stability analysis of this applications will be necessary for future research in microgrids stability.

2. The number of DGs and are increasing year by year, therefore the number of operating points and eigenvalues are growing, so the small-signal stability analysis should be analyzed from the statistics and data point of view in future research. The application of ANFIS is proposed in Publication V to train a virtual inductance block using data sets. The tuning of other controllers by virtual intelligence and using microgrid stable and optimal data will be a breakthrough in future research.

3. The application of ESS can change the dynamic modeling and small-signal stability of microgrids, this is not considered in this dissertation, but it is an interesting topic for future research.

4. The feasible ranges of VSG parameters and VI in presence of SIM loads and optimal values of these parameters have been proposed in Publication IV and Publication VI. The modeling of microgrid in presence of synchronous generators as conventional generating units and the interaction between converter-based DGs and these conventional generators can be a challenge in the microgrids and it requires further research in future.

5. The effect of PWM switching and possible unstable modes on the microgrids stability have not been considered in this research. This can be an interesting topic for future research.

6. The experimental test of the proposed intelligent control methods and sensitivity analysis of the control optimization performance to different levels of sensing and sampling errors introduced to the simulation data are proposed for future research.
References


The microgrid as a key building block of future smart grids includes distributed generations, loads, lines, and energy storage systems. The ongoing energy transition from conventional generations towards converter-interfaced renewable energy sources brings about several challenges such as microgrid instability, unfair reactive power sharing, frequency deviations, and poor voltage and current characteristics. This thesis proposes intelligent control methods for droop-based and virtual synchronous generator-based microgrids to deal with the aforementioned issues.