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ALTINBAŞ UNIVERSITY

Institute of Graduate Studies

Electrical and Computer Engineering

OPTIMAL DISTRIBUTED CONTROL FOR POWER SHARING IN AC MICROGRIDS

Mohammed Qasim Taha TAHA

Doctor of Philosophy

Supervisor

Assoc. Prof. Dr. Sefer KURNAZ

İstanbul, 2024

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2024

The dissertation titled OPTIMAL DISTRIBUTED CONTROL FOR POWER SHARING IN AC MICROGRIDS prepared by MOHAMMED TAHA and submitted on 03/06/2024, has been **accepted unanimously** for the degree of Ph.D. in Electrical and Computer Engineering.

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Assoc. Prof. Dr. Sefer KURNAZ

Supervisor

Thesis Defense Committee Members:

Assoc. Prof. Dr. Sefer KURNAZ	Department of Computer Engineering, Altınbaş University	____________________
Prof. Dr. Osman Nuri UÇAN	Department of Electrical-Electronic Engineering, Altınbaş University	____________________
Asst. Prof. Dr. Abdullahi Abdu IBRAHIM	Department of Computer Engineering, Altınbaş University	____________________
Asst. Prof. Dr. Serdar KARGIN	Department of Biomedical Engineering, İstanbul Arel University	____________________
Asst. Prof. Dr. Zeynep ALTAN	Department of Software Engineering, İstanbul Beykent University	____________________

I hereby declare that this dissertation meets all format and submission requirements of a Ph.D. dissertation.

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Mohammed Qasim Taha TAHA

Signature

DEDICATION

To my parents, wife, children, teachers, and friends,

I dedicate this thesis to my esteemed advisor, Assoc. Prof. Dr. Sefer KURNAZ, whose unwavering guidance, encouragement, and support have been the cornerstone of my academic journey. His patience and expertise have been invaluable throughout this endeavour. I also extend my gratitude to the members of the Thesis Monitoring Committee and Thesis Defence Committee. This work reflects the invaluable contributions of these mentors, for which I am deeply grateful.

ABSTRACT

OPTIMAL DISTRIBUTED CONTROL FOR POWER SHARING IN AC MICROGRIDS

TAHA, Mohammed Qasim Taha

Ph.D., Electrical and Computer Engineering, Altınbaş University,

Supervisor: Assoc. Prof. Sefer KURNAZ

Date: June / 2024

Pages: 137

Wide reformation in the conventional power grids towards a more sustainable and greener future depending on renewable energy resources (RESs). This has transformed power systems from national bulky centralized grids to microgrids (MG) with more autonomous controlling capabilities to be efficient in managing energy consumption. This resulted in a reduction in the carbon footprint and a resilient power transmission system. Inevitably, intelligent distributed control to maintain stability in MG and provide more reliable and cost-effective solutions is invented as a step towards wider energy supply coverage. Examining the effective and efficient distribution of power among MG distributed generators (DGs) is a crucial to develop advanced dynamic control methods to address the diverse challenges such as instability, sporadic features of RESs, fluctuating loads, and their interconnected power outputs. Coordinated energy management EM among interconnected DGs in energy exchange ensures stable operation and optimal power sharing (PS). Recently, several technical solutions have been proposed to tackle these challenges.

This thesis presents an adaptive control approach for enhanced PS in MGs utilizing the multi-objective Centripetal Force-Gravity Search Algorithm-Droop Optimization (CFGSA-DO). This approach requires each DG to exchange information with other DGs via a distributed communication layer to maintain energy balance in MG with high inertia response. The proposed optimization is briefed in the following steps: Objective Function Formulation: The formulation of the objective function involves defining a mathematical expression that captures the response criteria of MG concerning voltage and frequency stability. This function is designed to incorporate the essential parameters associated with droop control. Parameter Representation: Expressing droop control parameters in the optimization problem involves incorporating them as integral elements of the mathematical model, including droop coefficients and reference voltage/frequency levels. Fitness Evaluation: The iterative exploration of droop control parameter space is enabled by CF-GSA. This optimization method utilizes the concept of centripetal force to guide the search toward solutions meeting defined response criteria. Optimization Process: CF-GSA iteratively evaluates different sets of droop control parameters based on the specified objective function. Through multiple iterations, the algorithm refines its search moving towards optimal droop parameters values. Optimal Solution: Upon successful convergence of the optimization process, the resulting droop control parameter set represents the optimized configuration for stable MG operation.

This configuration is adaptable to variations in load and generation conditions, ensuring robust response across diverse scenarios. The proposed CFGSA-DO control optimization is simulated in MATLAB 2023a Simulink. The proposed work effectiveness is demonstrated under several practical, daily issues, and realistic cases that encountered the modelled radial MG. These cases include communication delays, generation disconnection, and load changes formulated to disturb power regulation in MG buses causing voltage and frequency (V-f) instability. The resulting results of PS optimization are validated, discussed, and proved superiority compared with previous experimental works.

Keywords: AC Microgrid, Power Sharing, Primary Control, Droop Technique, Communication System, Hierarchical Control.

ÖZET

AC MİKROŞEBEKELERDE GÜÇ PAYLAŞIMI İÇİN OPTİMAL DAĞITIK KONTROL

TAHA, Mohammed Qasim Taha

Doktora, Elektrik ve Bilgisayar Mühendisliği, Altınbaş Üniversitesi,

Danışman: Doç. Dr. Sefer KURNAZ

Tarih: Haziran / 2024

Sayfa: 137

Yenilenebilir enerji kaynaklarına (RES'ler) dayanan daha sürdürülebilir ve yeşil bir geleceğe yönelik geleneksel elektrik şebekelerinde geniş çaplı bir reform yapılmıştır. Bu, enerji sistemlerini ulusal büyük merkezi şebekelerden, enerji tüketimini verimli bir şekilde yönetmek için daha otonom kontrol yeteneklerine sahip mikroşebekelere (MG) dönüştürmüştür. Bu durum, karbon ayak izinde azalma ve dayanıklı bir enerji iletim sistemi ile sonuçlanmıştır. Kaçınılmaz olarak, MG'de kararlılığı sürdürmek ve daha güvenilir ve maliyet etkin çözümler sağlamak için akıllı dağıtılmış kontrol, daha geniş enerji arz kapsamına yönelik bir adım olarak icat edilmiştir. MG dağıtılmış jeneratörler (DG'ler) arasında enerjinin etkili ve verimli dağılımını incelemek, kararsızlık, RES'lerin düzensiz özellikleri, dalgalanan yükler ve bunların birbirine bağlı güç çıkışları gibi çeşitli zorlukları ele almak için gelişmiş dinamik kontrol yöntemleri geliştirmek için çok önemlidir. Enerji değişiminde birbirine bağlı DG'ler arasında koordine edilen enerji yönetimi (EM), kararlı bir işletim ve optimal güç paylaşımını (PS) sağlar. Son zamanlarda, bu zorluklarla başa çıkmak için çeşitli teknik çözümler önerilmiştir.

Bu tez, MG'lerde geliştirilen PS için çok amaçlı Merkezkaç Kuvvet-Çekim Arama Algoritması-Droop Optimizasyonu'nu (CFGSA-DO) kullanan adaptif bir kontrol yaklaşımını sunmaktadır. Bu yaklaşım, MG'de yüksek atalet tepkisi ile enerji dengesini korumak için her DG'nin diğer DG'ler ile dağıtılmış bir iletişim katmanı aracılığıyla bilgi alışverişinde bulunmasını gerektirir. Önerilen optimizasyon, aşağıdaki adımlarda özetlenmiştir: Amaç Fonksiyonu Formülasyonu: Amaç fonksiyonunun formülasyonu,

MG'nin voltaj ve frekans kararlılığı ile ilgili tepki kriterlerini yakalayan matematiksel bir ifadenin tanımlanmasını içerir. Bu fonksiyon, droop kontrolü ile ilgili temel parametreleri içerecek şekilde tasarlanmıştır. Parametre Temsili: Optimizasyon probleminde droop kontrol parametrelerinin ifade edilmesi, droop katsayıları ve referans voltaj/frekans seviyeleri dahil olmak üzere bu parametrelerin matematiksel modelin ayrılmaz unsurları olarak dahil edilmesini içerir. Uygunluk Değerlendirmesi: Droop kontrol parametre alanının yinelemeli keşfi, CF-GSA tarafından sağlanır. Bu optimizasyon yöntemi, tanımlanmış tepki kriterlerini karşılayan çözümlere doğru aramayı yönlendirmek için merkezkaç kuvveti kavramını kullanır. Optimizasyon Süreci: CF-GSA, belirli amaç fonksiyonuna dayanarak farklı droop kontrol parametre setlerini yinelemeli olarak değerlendirir. Birden çok yineleme boyunca, algoritma aramasını optimize droop parametre değerlerine doğru geliştirir. Optimal Çözüm: Optimizasyon sürecinin başarılı bir şekilde tamamlanmasının ardından, elde edilen droop kontrol parametre seti, kararlı MG işletimi için optimize edilmiş konfigürasyonu temsil eder.

Bu konfigürasyon, yük ve üretim koşullarındaki değişikliklere uyum sağlayarak, çeşitli senaryolar boyunca sağlam bir tepki sağlar. Önerilen CFGSA-DO kontrol optimizasyonu, MATLAB 2023a Simulink'te simüle edilmiştir. Önerilen çalışmanın etkinliği, modellerin radyal MG'sinde karşılaşılan birkaç pratik günlük sorun ve gerçekçi durum altında gösterilmiştir. Bu durumlar, iletişim gecikmeleri, üretim bağlantısının kesilmesi ve yük değişiklikleri gibi MG otobüslerinde voltaj ve frekans (V-f) kararsızlığına neden olan güç düzenlemelerini bozacak şekilde formüle edilmiştir. PS optimizasyonunun sonuçları, önceki deneysel çalışmalarla karşılaştırıldığında doğrulanmış, tartışılmış ve üstün performans kanıtlanmıştır.

Anahtar Kelimeler: AC Mikroşebeke, Güç Paylaşımı, Birincil Kontrol, Droop Tekniği, İletişim Sistemi, Hiyerarşik Kontrol.

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ABBREVIATIONS

AC	:	Alternating Current
ADMM	:	Alternating Direction Method of Multipliers
AI	:	Artificial Intelligence
ANN	:	Artificial Neural Network
BDC	:	Bi-Directional Converter
BESS	:	Batteries Energy Storage System
CC	:	Central Control
CF	:	Centripetal Force
CF-GSA	:	Centripetal Force- Gravitational Search Algorithm
CFGSA-DO	:	Centripetal Force-Gravity Search Algorithm - Droop Optimization
DAPI	:	Distributed Average Proportional-Integral
DAROSA	:	Distributed Adjustable Robust Optimal Scheduling Algorithm
DC	:	Direct Current
DER	:	Distributed Energy Resource
DESP	:	Distributed Energy Sharing Program
DG	:	Distributed Generator
DLT	:	Distributed Ledger Technology
DNO	:	Distributed Network Operator
DO	:	Droop Optimization
d-q	:	Direct-Quadrature Transformation
DR	:	Demand Response
DRE	:	Distributed Renewable Energy

DRL	:	Deep Reinforcement Learning
EM	:	Energy Management
EMS	:	Energy Management System
ESS	:	Energy Storage System
FOC	:	Fractional-Order Control
FRT	:	Fault Ride-Through
G	:	Diesel Generator
GSA	:	Gravitational Search Algorithm
HM	:	Hybrid AC/DC Microgrid
IBMG	:	Inverter-Based MG
IGM	:	Interactive Game Matrix
IoT	:	Internet of Things
LC	:	Local Control
MAS	:	Multi-Agent System
MG	:	Microgrid
MGC	:	Microgrid Cluster
MGCC	:	Microgrid Central Control
ML	:	Machine Learning
MMO	:	Multi-Master Operation
MPC	:	Model Predictive Control
PC	:	Primary Control
PCC	:	Point of Common Coupling
PS	:	Power Sharing
PSO	:	Particle Swarm Optimization
PV	:	Photovoltaic

PWM	:	Pulse Width Modulation
RC	:	Renewable Curtailment
RES	:	Renewable Energy Resource
RTO	:	Real-Time Optimization
SC	:	Secondary Control
SHM	:	Smart Hybrid MG
SMO	:	Single-Master Operation
SoC	:	State of Charge
SPOF	:	Single Point of Failure
THD	:	Total Harmonic Distortion
UPS	:	Uninterruptible Power Source
V-f	:	Voltage and Frequency
VFMT	:	Voltage/Frequency Management Technique
VMO	:	Vectorial MG Optimization
VSC	:	Voltage Sourced Converter
VSG	:	Virtual Synchronous Generator
VSI	:	Voltage Sources Inverter

LIST OF SYMBOLS

S_{nl}	:	No Load Generator Speed
S_{fl}	:	Full Load Generator Speed
f_n	:	Nominal Frequency
f_o	:	System Frequency
v_o	:	System Voltage
f^*	:	Rated Frequency
E^*	:	Rated Voltage
m_P	:	Power Droop Coefficient (*Hz/kW)*
n_q	:	Reactive Power Droop Coefficient (*V/kVAr)*
V_{ref}	:	Reference Voltage for DG Inverter
Q	:	Reactive Power
S	:	Apparent Power
Y	:	Admittance
$\mathcal{G}$	:	Graph
L_G	:	Laplacian Matrix
D_V	:	Generator Droop Voltage
D_S	:	Generator Droop Speed
T_c	:	Smoothing Time Constant
V_{nl}	:	Reference Voltage Under No Load
f_{nl}	:	Reference Frequency Under No Load
A	:	Adjacency Matrix
dP_l	:	Varying Load Power And

dP_i	:	Varying Generated Power
$\omega^{'}$	:	Post-Disturbance Frequency
ω_{MG}	:	Pre-Disturbance Frequency
fit	:	Fitness Value
fit_g	:	Iteration Fitness Value
Dis(x,x_g)	:	Distance Between The Search Agent And Global Optimum
X_i^*	:	Best Solution
X_i	:	Candidate Solutions Population
ω_c	:	Cut-Off Frequency
L_f	:	Impedance Filter Line Inductance
R_f	:	Impedance Filter Line Resistance
L_c	:	DG Line Inductance
R_c	:	DG Line Resistance
F	:	The Centripetal Force Acting Between Two or More Objects
U	:	Linear Velocity Of The Object
R	:	Distance Between Objects
M	:	Operational Scenarios Of An Objective Function
T_s	:	Regulation Time As An Objective
ω	:	Fundamental Frequency
v^*	:	Fundamental Voltage
ω_n	:	Nominal Frequency
P_n	:	Nominal Active Power
V_n	:	Nominal Voltage
v_{od}, v_{oq}	:	Measured Voltage

i_{od}, i_{oq}	:	Measured Current
ω_c	:	Cut-off Frequency
K_{iv}	:	Voltage Loop Integral Coefficient
K_{pc}	:	Current Loop Proportional Coefficient
K_{ic}	:	Current Loop Integral Coefficient
K_{pv}	:	Voltage Loop Proportional Coefficient
v_{id}^*, v_{iq}^*	:	SPWM Voltage
K_{SPWM}	:	PWM Gain
ω'	:	Post-disturbance Frequency
ω_{MG}	:	Pre-disturbance Frequency
U	:	The Object's Linear Velocity
R	:	The Spacing Between Objects
V_j	:	Distributed Generator Actual Voltage
V^*	:	Distributed Generator Nominal Voltage
N	:	The Number Of Distributed Generators
P_j	:	The Output Active Power
Q_j	:	The Output Reactive Power
P_j^*	:	The Reference Active Power
Q_j^*	:	The Reference Reactive Power
S_j	:	Distributed Generator Power Capacity
S_{Total}	:	The Total Load Apparent Power
P_{Total}	:	The Total Load Active Power
Q_{Total}	:	The Total Load Reactive Power

1. INTRODUCTION

1.1 REVIEW

Recently, our society has witnessed an unparalleled upswing in the need for electrical energy, propelled by timely urbanization, industrial expansion, and the pervasive influence of digitization. In response to escalating apprehensions about global environmental sustainability, Distributed Energy Resources (DERs), especially Renewable Energy Sources (RESs) have been targeted to be the main generation sources. These developments have led to a transformation in the traditional generation and distribution paradigms [1]. MGs, shown in Figure 1.1, emerging offer advantageous alternatives tackling power control and environmental issues and enhancing the electric distribution system. The difficulties in dealing with the uncertainties surrounding power generation, consumption, and prices pose a big challenge. These uncertainties are hindering progress toward realizing the full potential of the MGs.

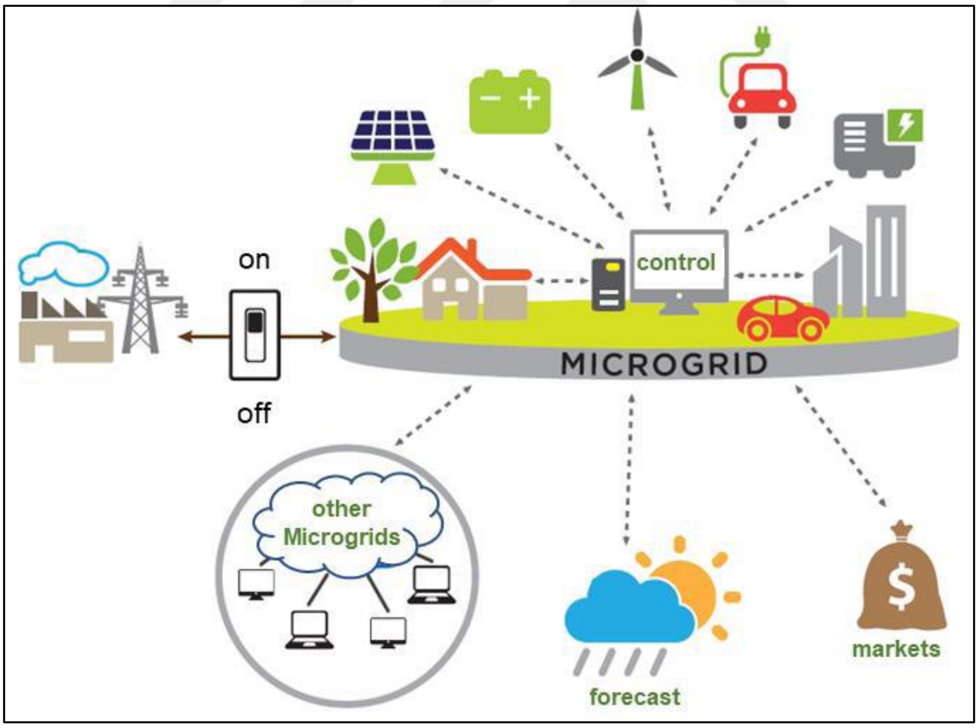

Figure 1.1: Prospectives of Microgrid Systems.

To make matters more practical, the grid code has imposed strict requirements that are challenging to comply with. It is imperative to have a unique Energy Management (EM) System (EMS) to meet all these standards simultaneously. [2] advantageous when trading in the energy market. There are several categories of MGs used according to the nature of the load and environment, as shown in Table 1.1.

Table 1.1: Microgrids Classification.

Categorization	**Types**		
Size	Small < 10 KW	Medium (10 – 1000) KW	Large > 1 MW
Operation	Grid-connected	Standalone (Islanded)	Transient Handling
Distribution system	AC	DC	Hybrid MG
Topology architecture	Radial	Ring	Mesh
Sources	Diesel	RESs	Mix

As shown in figure 1.2, MGs have gained increasing research significance due to their diverse advantages such us enhancing grid resilience, facilitating RES integration, and extending power accessibility to off-grid areas. Conceptually, an MG represents a localized integration of electric power sources and loads functioning as a unified and controllable entity concerning the overarching grid. The main grid manages the voltage – frequency (V-f) pattern of the connected MG [3]. MGs possess the capability to autonomously disconnect, presenting an opportunity to independently control and fortify their reliability, thereby mitigating grid disturbances. Typically, MGs comprise DGs such as photovoltaic panels (PV), wind turbines (WT), and diesel generators (G), and also incorporate Energy Storage Systems (ESSs) of flywheel or battery banks. However, the integration of variable loads and generators into a cohesive MG system poses technical challenges [4]. A fundamental challenge arises in the necessity for effective PS among MGs and the main grid, ensuring stability, during transient disturbances. The control of V-f holds the required importance for sustaining power quality and overall system stability. Traditional control strategies often fall short in efficiently tackling the dynamic and nonlinear nature of MGs. PS and voltage regulation is a major investigation area in MG control [5]. Under steady-state conditions, DGs operate at the same nominal frequency, and basic or enhanced droop control techniques control power regulation. However, harmonic power appears in DG power electronic conversion systems, with nonlinear and variable reactive loads and unequal feeder impedance conditions. Harmonic currents cause harmful power circulating in MG and lead to serious system instability.

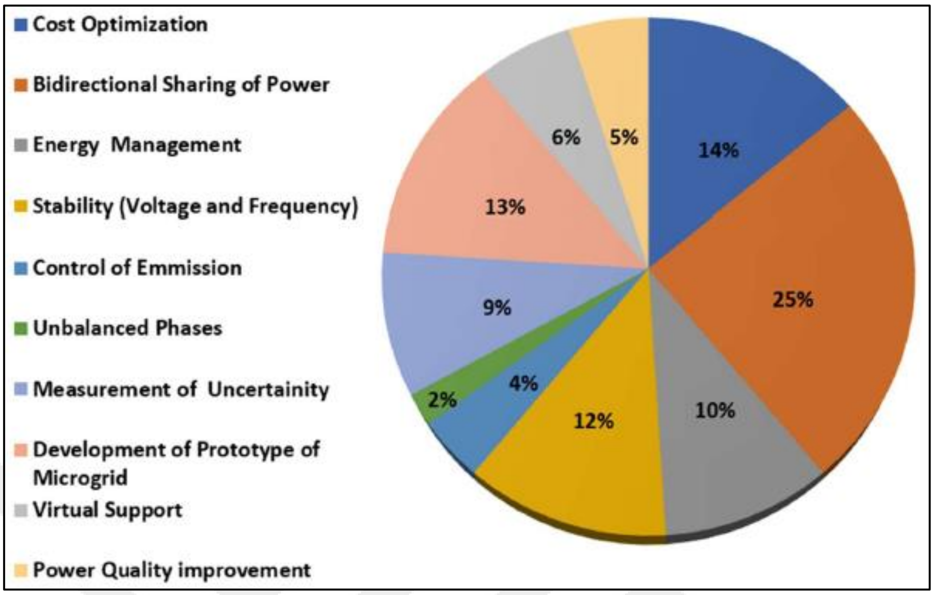

Figure 1.2: Literature Works Related to MGs.

Another reason for instability is faults in the transmission lines and generation units which lead to sudden disturbances in the power and voltage below or higher than the rated level. Therefore, regulating active power (P)- frequency (f) (P-f) droop schemes are used to encounter instability in small MGs since it is largely resistive and easy to control. In larger MGs, reactive power (Q) – Voltage (V) (Q-V) droop schemes are used to cope with the system and load impedance, which is mostly inductive. relationships schemes droop is practically favorable. Also, so-called virtual impedance control methods are combined with droop schemes invented to improve control response. The virtual impedance principle makes MG virtually inductive to increase the inertia of the sources by operating as a synchronous generator.

The droop and enhanced droops have shortcomings. The PS in droop schemes causes systematic V-f deterioration. Therefore, a Secondary Control (SC), monitoring, and corrective layer is required to compensate for the error among the nominal and bus voltages caused by the droop scheme, now called the Primary Control (PC) layer. The corrective steps go through the PI control to produce minimized error values. The PI-based conventional SC also deteriorates PS between MG nodes. Several strategies have been developed; some combine virtual impedance and adaptive droop [6]. The third layer existed is tertiary layer to ensure stability and more centralized coordination in MG with the smooth operation of different MG components. Frequency, voltage stability, P, and Q are all essential parameters to be shared among the systems and central control of the tertiary level, which is the final layer in this hierarchical system, and it interfaces MG and microgrid clusters (MGCs) to the main grid. Regardless of the SC ling scheme, whether centralized or distributed, tertiary is centralized or distributed.

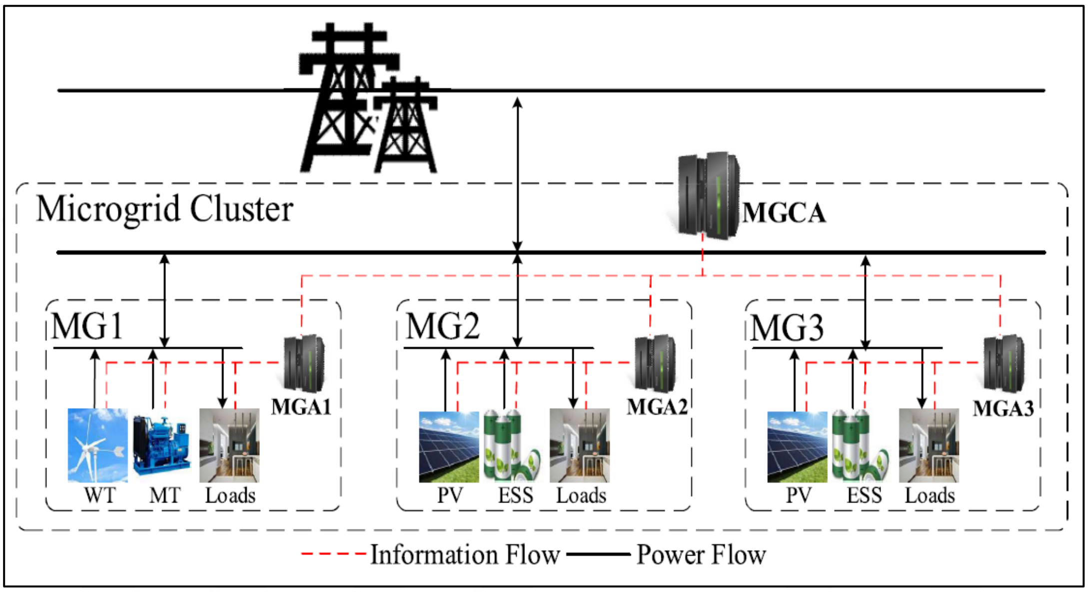

Figure 1.3: Microgrid Clusters Structures.

The hierarchical control system procedures are mainly used in MGCs, shown in Figure 1.3, to improve to regulate MG parameters effectively. Various methods enhance PS and voltage regulation in hierarchical systems. Optimal SC equations are achieved through programming algorithms that provide scheduled power references. Many Artificial Neural Network (ANN), Metaheuristic, and Machine Learning (ML) algorithms can be used to achieve these goals. Droop-based techniques, such as improved primary droop, virtual impedance, and hierarchical control methods, can ensure that power is shared evenly, and voltage is regulated throughout the system.

These promising methods will continue to develop and evolve, leading to safe, efficient, and reliable energy systems for all. One approach that has been used to distribute power is an adaptive voltage droop control. Another method is to combine droop and SC into one and coordinate the control over a sparsely connected network using distributed control methods. Smart droop can generate voltage references to exclude power and amplitude mismatch.

Also, a multiagent-based control system is utilized to control power grids, forming a group of agents that can make decisions. These methods promise proportional PS and voltage regulation [7]. AI and machine learning offer a potential solution to these challenges. AI is used to develop controls that adapt to changing conditions and optimize PS based on real-time data [8]. In this study, An AI-based droop control is implemented for an MG consisting of DGs. The goal of AI-managed PS among DGs optimally is controlling V-f levels within the accepted levels.

Therefore, the system aims to maintain stability and quickly restore normal operation following a disturbance. This research is significant because it contributes to understanding how AI provides a framework for enhancing grid resilience and stability using AI technologies. In the subsequent sections, we will explore the specifics of our system model, the design and functionality of the AI control, and the methodology used for testing its response [9]. In table 1.2. a literature survey of the most recent research works that received big attention in the community of MGs-enhancing researchers.

Table 1.2: A Literature Survey of Recent Research Works.

Authors & Reference	Goal	Method
(Farshadi & al., 2023) Reference [10]	Fault detection, during islanded operation, caused by reduced fault current levels.	Proposed a developed a protection algorithm for inverter-based MGs (IBMGs), to assess the protection robustness under various non-fault conditions.
(Khan & al., 2023) Reference [11]	Mitigating the energy poverty in remote rural areas through optimal power dispatch in islanded DC MGs.	Utilized second-order conic programming to optimize Power flow in PCC(PF), to minimize distribution losses using a modified IEEE-14 bus DC system.
(Quijano & al., 2023) Reference [12]	Optimized ESS operation in MGs for economic benefits, considering smart loads' and minimizing MG operation cost.	Proposed a price-based strategy, treating ESS-connected loads as rational agents, and adjusting consumption based on signals determined by MGCC.

Table 1.2: A Literature Survey of Recent Research Works “Table Continued”.

(Men & al., 2023) Reference [13]	Enhanced distribution system resiliency in dynamic MGs dominated by inverters to mitigate communication delays for computing average values of static and dynamic SC variables, establishing robust communication among DGs.	Proposed a fusion of SC levels among adjacent dynamic MGs on a 9-bus distribution feeder. Employ consensus-based algorithms.
(Nguyen & al., 2023) Reference [14]	Enhanced voltage ride-through (VRT) capability in grid-tied MGs during faults.	Proposed an effective inverter control hardware method mitigating VRT support and output current harmonics under grid faults.
(Adeyanju & al., 2023) Reference [15]	Proposed a strategy to assist Distribution Networks (DN) by prioritizing Peak Shaving (PHS), thereby lowering DN expenses and augmenting MG income.	Introduced a dedicated MG with a unique operational framework, considering short-term capacity, power purchase agreements, and PHS functionalities for profit optimization.
(Alvarez & al., 2023) Reference [16]	Optimized MG design for critical loads, considering RES reliability, and economic viability through the Vectorial MG Optimization (VMO) method.	VMO is proposed to streamline several aspects of MG design to integrate three key components: architecture selection, energy source sizing, and multi-objective optimization.
(K. Chen & al., 2022) Reference [17]	Enhanced islanded MG addressing uncertainties and customer resource constraints using optimal control with predictive current control.	Proposed a control incorporating predictive current control and mu-synthesis, ensuring robust MG stability.
(Fobes & al., 2023) Reference [18]	Enhanced MG resilience in electric grids during extreme situations, enabling service within and beyond MG boundaries.	Standardized quantification of grid-tied MG contributions through a declarative modelling approach.

Table 1.2: A Literature Survey of Recent Research Works "Table Continued".

(Polanco & al., 2023) Reference [19]	Alleviated rural energy shortages by implementing isolated MGs, reducing reliance on fossil fuels, and promoting sustainable energy solutions.	Established an IEEE working group to investigate MG feasibility. It developed a user-friendly web-based tool for MG planning using Django and Python; validated with users.
(Raman & al., 2023) Reference [20]	Enhanced MG resilience to false data injection (FDI) attacks by addressing timescale separation violations without additional sensors, preventing signal disruption.	Implemented a pre-determined lag compensator within the voltage consensus control to enforce time intervals, notably increasing the stability limit for manipulated signals.
(R. Chen & al., 2023) Reference [21]	Enhanced stability in MGCs during power shortages by developing an adaptive under frequency load-shedding strategy for uninterrupted power.	Proposed a composite LS-SVM-based load evaluation method, transforming critical load determination into a simple planning problem.
(Fan & al., 2023) Reference [22]	Implemented real-time optimal control in DC MGs to minimize cost by directly applying dynamic reinforcement learning (DRL), to avoid periodic optimization mismatches.	DRL is used, specifically TD3-based optimal control, without explicit system modelling, discovering state-action links through interactions, ensuring real-time distributed control efficiency in DC MGs.
(Liang & al., 2023) Reference [23]	Enhancing the hybrid efficiency (AC/DC) MG (HM) using bi-directional converters (BDCs) via a data-driven convex model.	Develop a convex linear HM model by linearizing BDC efficiency through a least squares approximation with data-driven weight functions.
(Thanh & al., 2023) Reference [24]	Enhanced critical load resilience in commercial MGs during extreme events by optimizing proactive scheduling for comfort and cost.	Proposed a two-layer framework integrating data-driven models (LSTM, fuzzy neural network) and deep-Q network to ensure solutions' robustness under uncertainties in extreme events and anomalous data.

Table 1.2: A Literature Survey of Recent Research Works “Table Continued”.

(Song & al., 2023) Reference [25]	Enhanced power electronic system reliability, reducing end-of-life maintenance costs.	Adaptively adjusted droop gains based on accumulated device damage and considering nominal power of active droop gains. Validate through experiments and simulations, estimating lifetime.
(Kumar & al., 2023) Reference [26]	Enabled bidirectional power transfer among islanded hybrid MGs, ensuring constant rated voltages for different MGs under various scenarios.	Utilized bidirectional converters dc-dc and three-phase VSCs, proposed feedforward and feedback signals for control, validated through simulations.
(Banerjee & al., 2023) Reference [27]	Achieved resilient MG restoration using DERs and smart communication-less circuit breakers, validated in simulation and hardware testbed.	Employed instant intelligent sensing and decision-making for self-sufficient islanded MG reconfiguration, utilizing grid-establishing inverter modules and intelligent circuit interrupters.
(Sitharthan & al., 2023) Reference [28]	MG stability by EM	Internet of Things (IoT) has been used with MG for EM and analysis
(P. & al., 2022) Reference [29]	The concept of DER Sharing (DES) facilitated energy sharing among PV prosumers in a Smart Hybrid MG (SHM).	The Internet of Things (IoT) establishes communication between SHM and PV prosumers, or vice versa, thereby facilitating an efficient and cheap exchange of energy.
(He & al., 2023) Reference [30]	To allow MG to cope with the uncertainty of source load.	PCC frequency regulation method based on DRL, TD3-based frequency regulation method
(Bhatt & al., 2022) Reference [31]	Transforming a traditional MG to a smart MG	A data-driven decision-making strategy based on response evaluation of various wireless networks to optimally build SMG.

Table 1.2: A Literature Survey of Recent Research Works "Table Continued".

(Dinesha & al., 2022) Reference [32]	The research under consideration explores the potential for creating blockchain SMGs (BSMG)	Blockchain, functioning as Distributed Ledger Technology (DLT). It serves as a ledger system wherein transactions involving different entities, including energy information, and money, are maintained.
(Karimi & al., 2023) Reference [33]	To consider the aggregate generation costs, the flexibility of generation resources, and the flexibility on the demand side.	A model has been constructed utilizing datasets. A hybrid approach, integrating both maxes–min and min–max strategies, has been devised to standardize the load profile via demand management.
(Dehghani & al., 2022) Reference [34]	Proposed study to improve the steady-state response of the three MGs regarding total harmonic distortion (THD), maximum value, and effective value in voltage regulation mode.	A flexible benchmark has been devised and utilized instead of a consistent reference signal to improve the system's stable-state operation.
(Carli & al., 2020) Reference [35]	Energy scheduling program to reduce the energy cost in smart grid.	Loads of an MG supplied from a PV station are simulated based on a year dataset with a 1hr resolution to obtain the control model process.

For safety and quality energy supply, engineers ensure that control design meets governing standards, effectively guaranteeing risk-free use of MGs [36]. The necessary MG standards have been listed and discussed to provide an overview of the relevant technical specifications that MGs must meet.

It is important to respect MGs' load-MG coupling standards constraints, considering factors such as harmonic generation, voltage unbalance, voltage, and frequency regulation. Adherence to electrical standards is imperative for ensuring safety and quality assurance.

Table 1.3 summarizes a collection of leading electrical standards applied in the European Union grid and essential for MG control design [37].

Table 1.3: The Electrical Standards of MGs Control.

Standard	Application	Standard Rules Description
IEC 61851	Electric vehicle (EV)	The voltage levels are accommodated for home EV charging, capable of handling up to 250V in single-phase and 480V in three-phase MGs
IEC 60364-1	Human Safety	The nominal voltages ensure the safety of individuals against potential life-threatening hazards. The installation should be capable of handling up to 1000V AC or 1500V DC to guarantee this safety.
IEEE 2030.10	DC off-grid energy providers	48V DC bus is recommended as a low DC voltage bus system used in isolated communities to ensure efficiency and safety.
IEEE 1547	MG connection with the main grid	Rules of safely and efficiently integrating DERs (< 10 MVA) in the grid, including power quality, MG reconnection, and maintaining rated frequency and voltage at PCC.
IEC 61000 IEEE Std115	Electromagnetic Compatibility	Govern the AC power quality limits where voltage unbalance is limited to less than 3%.
IEEE Std 1709	Medium Voltage (MV) bus	To cope with the maximum ripple and DC voltage deviation tolerances, govern the DC power quality to be between (1.5kV and 35kV).
IEEE 2030.7	EMS	Governs the EMS of MGs regardless of the topology.
IEC 61850	Utility Automation	Governs the communication configurations in MG

There are many differences between AC and DC MG, as shown in Table 1.4, DC MGs experience a reduced power quality complexity and fewer power converters, whereas AC MGs need more attention regarding grid synchronization and frequency regulation. These different factors can profoundly impact the total response of these systems. Consequently, remote areas can benefit from DC MGs due to their power quality and limited power converters. However, the grid-connected MG's reliability is enhanced by using bidirectional interlinking converters.

Table 1.4: Comparison of AC and DC Microgrids.

Comparison Points	AC Microgrid	DC Microgrid
Direct integration of RESs (such as PVs) and electric vehicles without the need for a DC-to-AC converter	No	Yes
integrating the DC/AC converter need and the ESS into a single package	No	Yes
Integration of DC load	No	Yes
Control and characteristics of power quality in a microgrid	More complexity	Easy
Control of frequency	Yes	No
Synchronization	Yes	No
Skin effect	Yes	No
Protection Methods	fully realized methods, not costly	Still in the early stages of development and costly
Standards	Adequate and highly developed	Not sufficient
System cost	Low	High

Therefore, hybrid MGs have emerged as a combined DC simple bus and AC flexible and dependable buses [39]. It has been observed that various standards, as shown in detail in Table 1.5, are considered depending on MG capacity [38]. More details regarding this topic are provided upon request. Notably, there exist differences between DC MGs and AC MGs. The validity of the potential impact of investment in MGs with multiple distributed generators has been assessed as crucial. The successful implementation of this transition necessitates a more distributed and autonomous control and scheduling system. This shift from a centralized structure has been deemed necessary due to concerns surrounding privacy, network vulnerabilities, and the possibility of central control failure with the addition of more DGs.

Table 1.5: Typical Voltage Level of Microgrid PCC Bus.

MG type	Application	Standard	Voltage Level (V)	Tolerance Level
AC	Grid-connected hybrid or AC MGs	IEEE 1547	230/400	Voltage: ±5% Frequency: ±0.2 Hz
DC	Remote Off-grid buildings	IEEE 2030.10 IEC 60038	48	Maximum Current: 5A ()
	Grid-connected buildings	IEC 60038	380–400	Supply terminals: ±10% Equipment terminal: ±4% ()
	Industrial applications	IEEE Std 1709	1500(±750)	DC level: ±10% Ripple: ±5%

The importance of having a strong and dependable method of distributed control and management algorithm for MGs with multiple distributed generators cannot be overstated. As distributed generators are in various locations, ensuring overall MG stability, security, and scalability is crucial. This is essential to guarantee the investment's validity and potential impact on MGs. A more robust and reliable system is needed to ensure MG operates without privacy concerns, network vulnerabilities, or single-point (central control) failure [40]. Therefore, CFGSA-DO control offers an effective solution for the challenges associated with MGs with multiple distributed generators. PS mainly contributes toward better voltage/frequency stabilization. Reactive power sharing (RPS) limitations need more investigation to be solved. Therefore, the conventional droop-based algorithms offered the most effective solution since droop controls are simple, external communication free, decentralized, and have acceptable inertia response. Integrating virtual inertial loads with droop inverters has been proposed to create a control system able to fulfill the swing equation and behave similarly to traditional generators during transient conditions. These inverters are Virtual Synchronous Generators (VSG). While conventional droop-based control algorithms have their appeal, they also come with significant drawbacks. This is especially evident in MGs with low X/R ratio distribution lines that are ohmic, even though distributed generators' outputs are mainly inductive [41]. While this impedance mismatch has a limited impact on PS, it leads to poor PS and serious stability concerns. Thus, the DG’s impedance is virtually adjusted, but optimal and stable PS requires external communication due to the influence of load changes on MG's X/R ratio.

The application of CFGSA-DO as a PC control represents an enhancement to conventional droop control, offering improved response with minimal communication requirements. This modification is aimed at addressing the precise sharing of Q among DGs within MGs. The methodologies for addressing this issue are categorized into decentralized, centralized, and distributed approaches, as well as hybrid control algorithms.

Centralized control systems in MG studies employ mixed-integer linear, genetic, and particle swarm algorithms. However, these systems necessitate high communication requirements, reducing efficiency with increasing DG numbers. The concept of decentralized control systems has undergone extensive exploration, primarily focusing on integrating virtual impedances into the distributed generator outputs. In this approach, each distributed generator assesses the impedance of its respective PCC and adapts its virtual impedance to align with it [42] accurately.

However, this technique encounters limitations such as increased voltage drop and inefficiency when multiple DGs are in play. This stems from the assumption that each DG feeder possesses a comparable impedance profile. The impedance mismatch and circulating currents arise due to DGs’ disparate ratings and sizes. Thus, complex control and communication systems are necessary to implement decentralized control algorithms properly. Therefore, without smart control, there is a need for bulk communication and control equipment to maintain operational efficiency even when incorporating multiple DGs within MG. The optimized droop has undergone investigation to reduce communication and information bulk exchange requirements. These predictive algorithms leverage a linearized model to anticipate the power requirement and regulate DG output accordingly. Also considered are 'Agent-based algorithms,' which entail a three-step communication process among DGs and their neighbors to maintain adequate power level [43]. Also, Decomposition algorithms, invented and utilized, involve breaking down the original Q optimization task into subtasks by grouping specific DGs and achieving iterative convergence. Compared to the algorithms mentioned, CFGSA-DO control is simp to work with minimal communication requirements and a shorter convergence time, and it is not a single-point failure system.

1.2 MOTIVATION

Energy has gradually developed into an indispensable aspect of human existence. From everyday household items to complex industrial facilities, all these entities rely on energy for operation. Consequently, it becomes crucial to effectively generate and regulate energy to ensure its stable and reliable delivery to end users. The escalating concerns regarding global warming due to fossil fuel emissions and the diminishing fossil fuel reserves have prompted researchers worldwide to focus on identifying cleaner, more efficient, and dependable energy sources.

This shift in focus is gradually steering energy sources toward greener and environmentally friendly alternatives. Furthermore, DGs have played a transformative role in abundant and green energy resources. RESs originate from diverse natural phenomena such as solar, wind, wave, tidal, geothermal, and biofuel energies. In contrast to traditional fossil energy, RESs adeptly capture energy in modest and intermittent amounts. Nevertheless, these resources are strategically deployed across extensive territories, challenging their poor adaptability and installation costs. RESs offer cleanliness, accessibility, fuel-free, fuel transportation costs-free, and exhibit unreliability due to their dependence on varying weather conditions and times of day [44]. This challenge is aggregated by the ongoing advancement in electrical system efficiency, posing complexities to the dependability and integration of DGs or DERs. These modern generators, small in scale yet efficient in response to form MGs as compact electric networks. However, the pressing concern lies in comprehending these MGs' integration, control, and stability, which remains under active research. Including DGs within power distribution systems offers an avenue for achieving cost-effective and efficient centralized control of power dispatch. Various strategies for Q control have been proposed, rooted in Lyapunov functions that utilize locally measured parameters to mitigate system voltages. Nonetheless, a thorough stability analysis concerning minor signal deviations and complete droop control within autonomous MGs could be more efficient. It has come to light that Q distribution proves ineffective amidst notable load fluctuations, prompting a need for further investigation to address this issue.

Considering these challenges, CFGSA-DO control theory emerges as a promising avenue for exploration. CFGSA-DO control involves adaptable analogous autonomy that requires less interaction and communication with connected DGs and loads, rendering the system resilient and dependable even amid substantial load changes [45]. It mirrors the operation principles of synchronous generator control. Despite its effectiveness in regulating Power (P) distribution and managing frequency, this method fails to ensure grid voltage stability and efficient sharing of Q, ultimately leading to grid instability.

1.3 THESIS OBJECTIVES

a. It reviews the various emerging control structures invented to keep allowable voltage transgression that arises in typical MGs with varying penetration of RES.

b. This study aims to design CFGSA-DO for PS among DGs within MG. Also, the research aims to demonstrate that this control approach guarantees stable voltage levels within each PCC and the main PCC in MG under many challenging conditions.

c. Identify MG’s practical cases to support the theory assessed in the previous objective, including the simulation of a monitoring/control architecture of MGs to develop and simulate a prototype MG to prove the effectiveness of CFGSA-DO control.

d. This research has analyzed PS convergence within MG, considering various communication topologies commonly employed in typical MGs.

e. It examines the consequences of communication failure.

f. Testing the response under DG tripping within and MG and observing the effective response of the proposed system of keeping the V-f within tolerant values at MG and DG buses.

g. Testing the response under the sensitivities of CFGSA-DO control gain and the influence of varying loads connected to MG.

1.4 PROBLEM STATEMENT

MG involves renewable energy resources, whose intermittent nature induces fluctuations in their maximum power capacities. Furthermore, MGs possess the capability to function in conjunction with or independently from the main grid, exhibiting a dynamic imperative to ensure a harmonious equilibrium between the demands and origins of power within the entire cluster.

In addition, the interconnection of multiple power units within the same MG necessitates the efficient allocation of PS across numerous nonlinear sources and loads, causing speculating harmonic power in the ring of local DG buses. This imperative for equity extends to the MG control structure, demanding the dynamic adaptation of PF to ensure parity in PS, thereby optimizing the aggregate available power to meet the load power requisites involving the entire MG. The V-f stability enhancement is realized by applying droop control and optimization methodologies, a technique utilized to facilitate PS among parallel DGs. It is imperative to note that traditional droop control mechanisms exhibit limitations in accurately distributing output current and power among inverters.

1.5 PROPOSED WORK

To address the above problem, PS concept must be developed and enhanced; MG is structured into several DGs, each using primary and SC levels to manage stability and power balancing. The distributed PS control of locally controlled inverter based DGs in MG is needed. DG is required to generate power in proportion to the fluctuations of MG. The proposed work is to enhance P-f response (Frequency- Power Restoration). Due to significant loss of generation or load power or to correct forecast errors, tertiary control is activated to relieve SC. Since power imbalances are negative or positive, Tertiary control is activated for upward and downward regulation.

The redesign of SC and PCs is required to meet the needs of tertiary regulation, as the power system cannot handle power imbalances alone. During the change in power capacity of a DG, CFGSA-DO control activates, employing a simplified communication layer to estimate the corresponding change in MG. Investigating CFGSA-DO aims to ensure optimal power distribution in PCC with varying power capacities, enhancing system robustness and reliability against significant load and generation fluctuations. The study will analyze the impact of time delays to ascertain their effect on stability. Stability hinges solely on local processing time delays of DGs, while communication delays between DGs affect the convergence rate. Simulation outcomes corroborate the stability margin of time delays in an AC MG comprising four DGs and multiple loads.

1.6 COMPARISON

Load-shedding and curtailment strategies are commonly employed mechanisms in autonomous single MGs to mitigate transient overloading and excess generation. However, tackling these challenges within MGs for effective PS presents a complex and prominent research area. While achieving APS in a single MG remains feasible under varying conditions, ensuring effective PS among DGs in an MG poses significant challenges. This proposal introduces a control scheme that guarantees efficient PS between distributed generation units to address this. A framework based on novel multiagent moving average estimators is proposed to facilitate the sharing of real and Q among participating nodes, ensuring improved power management and stability within MG. In this dissertation, a novel CFGSA-DO control is introduced and validated to provide a stable MG response. It optimizes power balancing and sharing, substantiated through numerical simulations and experimentation. The main thesis objective is to devise a control strategy spanning all three control layers. This strategy facilitates effective PS across multiple bi-directional power converters of MG. PS challenges necessitate a strategic approach to attain EM and distribution. CFGSA-DO control is a suitable control mechanism to realize PS amongst MG clusters regulating the power within and between MGs.

1.7 OUTLINE OF THESIS

This dissertation structure is presented as follows:

a. Chapter 2 reviews MG control background, structure, operation, and communication. It will also introduce the concepts of each control layer, communication layer, overall MG electric model and control structure, graph theory, and other theories.

b. Chapter 3 elucidates the process of modeling an MG and describes the software employed for conducting simulations. Also, this chapter involves a detailed exploration of the proposed control's challenges and the underlying mathematical dynamics.

c. Chapter 4 presents, discusses, validates, and analyzes the proposed model results. This chapter delineates the presentation of the effectiveness of CFGSA-DO control under various simulated scenarios.

d. Chapter 5 describes the entirety of the thesis contribution, depicts the efficacy and advantages of the proposed CFGSA-DO control, and outlines the prospects for future potential.

1.8 SUMMARY

The concerns regarding MGs' voltage, frequency, and power stability persist due to the need for more conventional droop control with distributed generators. This issue is expected to exacerbate with the growing integration of RESs. Since the CF-GSA algorithm was proposed, it has succeeded in various domains of power regulation, and its application in MG PS control poses a promising solution. This Dissertation proposes a developed model for an MG distributed control, conducts simulations for CFGSA-DO control to enhance PS among DGs distributed in MG under varying grid conditions, and demonstrates this control approach's practical viability.

2. LETRATURE AND RELATED STUDIES OF MICROGRIDS

This chapter explains the theory and literature of MG's control structure, operation, communication, and smart schemes. The mathematical relationships involved in each aspect of MG will also be presented and discussed in this chapter. To understand this thesis work, it is essential to know the exact nature of MG and how PCC bus V-f is controlled to ensure stabilized, reliable operation. The PS in MG structures requires first uncovering the details of conventional control schemes included in the hierarchical system, such as how primary droop and SC layers equations have been derived. Finally, diving deep into the literature of communication and AI involved in the proposed approach aiming toward optimal PS.

2.1 WHAT IS A MICROGRID

MG is described as a collection of controlled DGs, ESSs, and loads. It operates in both autonomous or grid-tied modes and connections with either an MGC or an extensive power grid, Figure 2.1 depicts the configuration of a typical MG. DGs exhibit diverse types and ratings, they cover both conventional reliable fueled generators or RESs that are safer and cleaner but nature-dependent intermittent sources. Within the kilowatt range, DGs, often owned by utility customers, contribute to MG generation requirements.

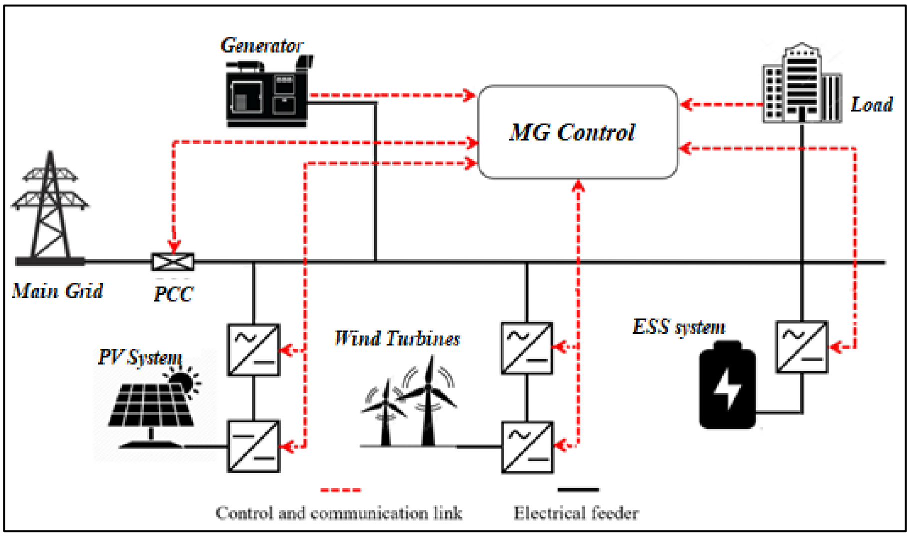

Figure 2.1: Typical Scheme of Typical Microgrid.

DGs are incorporated and detached within a 'Plug and Play' framework. This implies that individual DGs can connect or disconnect from MG without affecting grid-connected generators' control or protection system. To enable MG to function as a singular electrical system that upholds electrical grid parameters, all DGs, irrespective of their energy source, necessitate power inverters for integration. This imparts total MG with essential flexibility and control. Besides addressing DGs' integration and interface challenges, and inherent protection concerns, time-variant loads challenge, MGs must involve a complex reliable control system able to regulate PF, ensuring voltage stability, by distributing power among DGs.

2.2 CONTROL STRUCTURES OF MICROGRID

Diverse control techniques for MG technology have been proposed, contingent upon its operational and application domains. An extensive literature review has been conducted in this chapter. The spectrum of MG controlling methods is categorized into two categories: Droop and miscellaneous control techniques [46]. This categorization is depicted in Table 2.1.

Table 2.1: The Control Techniques of MGs.

Droop Control Techniques	**Miscellaneous Control Techniques**
Conventional Droop Control	Model Predictive Control
Optimized droop Control	Fuzzy Logic Control
Combined Droop Control	Artificial Neural Network Control
Networked Droop Control	Linear Quadratic (Integrator, Regulator)
Hierarchical Droop Control	Deadbeat, Repetitive, Hysteresis, H-infinity control

Networked control systems play a role in ensuring stability and enhancing the transient response of feedback control loops, covering parameters such as current, voltage, frequency, phase, P, and Q. This significance extends to both islanded, isolated, and grid-connected modes. The hierarchical architecture includes multiple operational layers, each assigned specific functions:

a. Supports DG coordination and load sharing.

b. Supports V-f regulation in any operating mode.

c. MG resynchronization with the main grid line at the PCC point.

d. Power flow control with neighborhood DGs, and in the main grid.

There are control support communication topologies that send signals in MG systems. Depending on the topology of information exchange, MG is categorized into distributed, centralized, and hybrid [47]. This characterization is depicted in Figure 2.2.

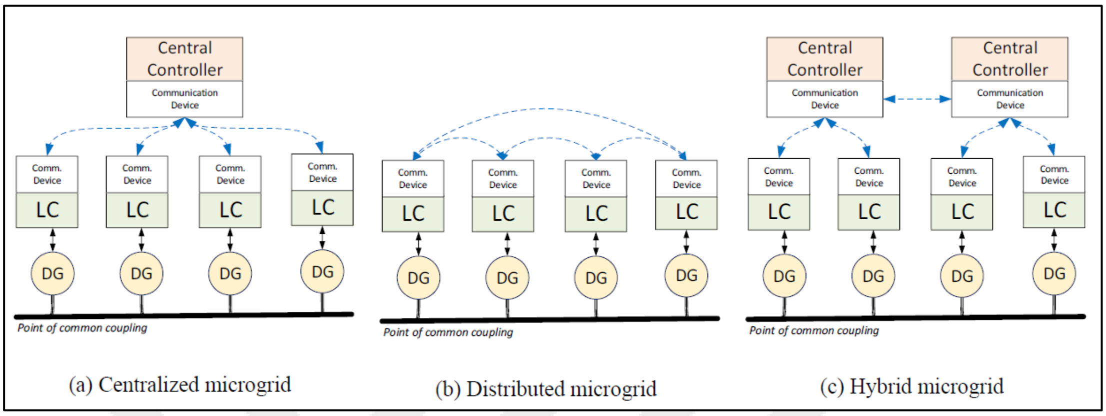

Figure 2.2: Conventional Topologies in MGs Communication Control Architecture.

Robust control structures are recommended to ensure optimal V-f stability within an MG, thereby promoting MG operation with enhanced reliability and economic objectives. Otherwise, ESSs and generators facilitate fast, dynamic, and dependable electrical energy with high inertia and low control requirements. Therefore, the control of its constituents is categorized into two types:

a. Local Control (LC): It is situated in proximity to local loads; positioned adjacent to DGs.
b. Central Control: It is employed in centralized control [48], plays a pivotal role in receiving, analyzing, transmitting, and controlling command signals, adhering to the centralized control approach.
c. Distributed Control: It is located at each component of the system like LC but take information from all other components like centralized control.

To optimize power flow, MGCC signals are relayed to LCs and load control. However, notable limitations lie in its high dependence on communication techniques, high information exchange, and single-point failure since it is a single entity striving to optimize economical and operational criteria for the entire system. However, the decentralized control strategy functions autonomously, regardless of MGCC and the communication infrastructure. In this approach, each LC plays a pivotal role in enhancing MG stability by assessing and responding to local parameters. Furthermore, the distributed control strategy, which is both dispersed and integrated, establishes connections between the LCs and MGCC.

The centralized, decentralized, and distributed strategies result in the formation of a hierarchical control system with three layers: PC, SC, and tertiary control. Within this hierarchy, the primary level exhibits the response time, addressing MG parameter fluctuations to uphold these parameters within the acceptable range for ensuring stability. SC level concentrates on rectifying steady-state errors related to voltage, frequency, and PQ. This level possesses the capability to offset deviations in V-f inherent to droop control. Finally, the tertiary level, situated at the apex of the hierarchy, assumes the role of global control within the MG system [49]. However, it operates with a comparatively slower response time, engaged in mitigating economic and market-related challenges. An elucidation of this hierarchical control system will be provided in Section 2.4.

2.2.1 Centralized Strategy

In this framework, the supervision of MG variables is placed under the purview of a main control [50]. This control relies on data acquired from an array of positioned sensors within MG. The responsibility of central control is the brain of the MG stabilization and regulation process, thereby introducing the potential vulnerability of a single-point failure. Also, the endeavor to integrate RESs and DGs through a plug-and-play framework is facing inherent challenges. Furthermore, the substantial demands of data collection contribute to increased network bandwidth requirements and necessitate elevated availability prerequisites.

2.2.2 Decentralized Strategy

In this paradigm, LCs operate independently, without the need for direct communication [51]. The exclusive demand for network connectivity is associated with top-level control, which receives reference values from a central control. This approach reduces the costs linked to network communication and enables the seamless integration of new devices through plug-and-play mechanisms (e.g., droop control), achieving optimal response among LCs. Furthermore, CFGSA-DO control is constrained to achieving specific control objectives.

2.2.3 Distributed Strategy

To address the limitations of prior approaches, this strategy proposes integrating control collaborating to achieve overarching control objectives [52]. This arrangement eliminates the presence of a single point of failure (SPOF), thereby improving MGs reliability. However, despite its merits, several complex challenges demand attention. This complexity arises since both network communication constraints and stability requirements in distributed strategy play pivotal roles in distributed control.

2.3 MICROGRIDS STRUCTURE AND OPERATION MODES

MGs integrate a wide array of DER resources, including WT, PV panels, Fuel Cells, Micro Turbines (MT), and ESSs such as supercapacitors, flywheels, and batteries, along with manageable loads [53]. This combination empowers them with robust control capabilities for local network operations. These systems possess the flexibility to be incorporated into the low-voltage distribution network or to transition to an islanded mode in case of primary network faults. In grid-tied mode, the MG system operator must ensure better RES involvement with adequate MG operation optimization. This entails meticulous consideration of control functions to achieve peak response in the connected mode. MG system operator employs various factors, including load predictions (electric and thermal), capacity projections (derived from local generators), energy prices, gas expenditures, local generation potential, local load requirements, grid security considerations, and distribution network prerequisites to determine the amount of power drawn from owned DGs and the energy exchanged with the grid. Non-essential manageable loads are disconnected when required, and vigilance over the PS is required.

These methodologies are equated to SC mechanisms found in conventional power networks [54]. The fundamental configuration of an MG operates in both islanded and grid-tied modes. The grid-tied mode presents complexities due to the necessity of catering to local loads within MG while transmitting power to the main grid. MGCC takes charge of the DG units during grid-connected operation, when additional loads or sudden islanding events impact the network, resulting in voltage drops or frequency oscillations at PCC [55]. An illustration of a standard MG architecture, alongside LCs and MGCC, is illustrated in Figure 2.3.

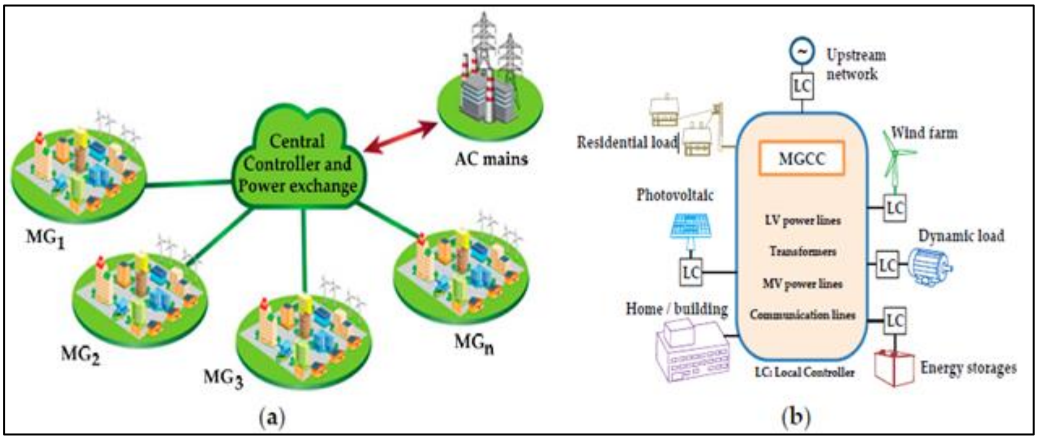

Figure 2.3: (a) Microgrids EMS and Upstream Network, (b) Local Equipment of Typical MG.

In islanding operation mode, RESs provide power to local loads and regulate V-f. PCC bus bar, which is interconnected with the upstream network during the connected-to-network mode, plays a crucial role in managing PF and load distribution between MGs and the upstream network. Ensuring MG stability is of required importance, necessitating a suitable control strategy to address real-time power demands amidst continuous load fluctuations of varying characteristics. Thus, it is imperative for DGs to possess the capability to supply P and Q, thereby constraining deviations in MG V-f. Among the well-established control mechanisms in this domain, droop control has had wide utilization in recent years. Due to the absence of droop characteristics in inverters, an artificial droop and inertia control system is devised to enable grid-connected inverters to emulate the operation of synchronous generators. These VSGs are control approach operating according to the fluctuation limits introduced to govern the network's transient and steady-state conditions [56]. Given the influence of DG units' inertia on droop control, VSG allocates the generation among DG units to preserve its virtual inertia and coordinate with other DGs.

2.4 HIERARCHICAL CONTROL

The hierarchical MG control framework is shown as comprising multiple task levels. As depicted in Figure 2.4, these levels are involved in functions such as sensing, processing, monitoring, adjusting, supervising, maintaining, and optimizing tasks. It is categorized into four levels. The initial stage is PC for source operation regulation, and this is accomplished using power electronic inverters/converters [57]. The control is achieved through inner droop control loops, focusing on the management of DG output power. PC acts to address fluctuations at the millisecond scale thereby providing the fastest response. PC level aims to modulate reference values derived from V-f amplitudes, consequently supplying inner loop input. Oversight and monitoring of V-f require the primary responsibilities at the SC level. In practical terms, when variations occur in load or generation within MG, SC ensures that deviations are constrained within specified limits, such as Nordel (North of Europe) ± 0.1 Hz or UCTE (Continental Europe) ± 0.2 Hz [58]. In comparison to PC, SC exhibits a dynamic response to variations. The classification is divided into decentralized and centralized controls, elaborated in the following sections. The third control level, the ultimate and slowest, supervises the voltage-frequency (V-f) of MG linked with the main grid. This regulation depends on grid P and Q measurements. The implementation of MG control strategies proves to be efficient and effective when deployed across various operational levels, catering to multiple objectives, and ensuring the reliable, secure, and cost-effective operation of MGs, whether in grid-connected or islanded mode. The pertinent tasks in control and protection is summarized as follows [59]:

a. Ensuring rapid response to system variations.
b. Supervising and maintaining V-f.
c. Regulating deviations within defined limits.
d. Maintaining stable V-f in grid-connected MGs.
e. Implementing efficient multi-objective control strategies for reliable MG operation.

The points above can tackle the following challenges in MG response:

a. Uncertainties
b. Low inertia
c. Bidirectional power flow
d. Dynamic modeling and stability

On the contrary, the control objectives embedded in MG control system involve various crucial facets, including voltage regulation and PS, V-f control, management of Demand Response (DR), economic dispatch, and the seamless transition between operational modes. In grid-connected operation, significant considerations revolve around the interaction with the main grid, while in islanded operation, the focus shifts to heightened reliability and more pronounced control challenges due to MG's limited inertia.

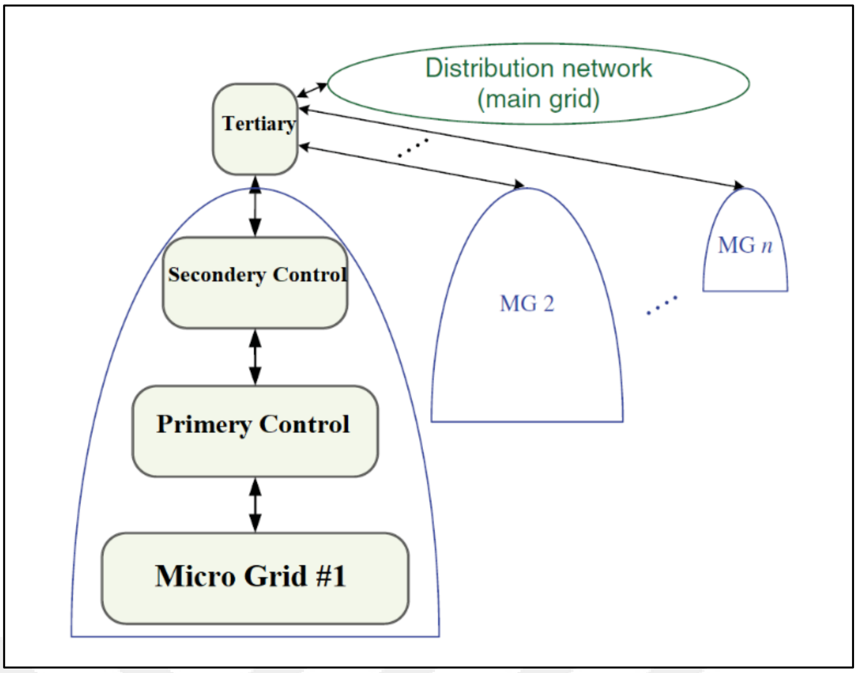

Figure 2.4: Microgrid Hierarchical Control Layers.

The islanded mode introduces operational challenges [60]. In a broader sense, instabilities within MGs manifest in the following manner:

a. Small signal instability: This type of instability arises from various recurring factors, involving the dynamic effects of continuous load fluctuations, feedback control, oscillation modes, and DGs' power constraints.

b. Transient Instability: Transient instabilities are provoked by unexpected islanding events, DG failures, substantial and abrupt load variations, and cascading faults.

c. Voltage instability: Challenges in voltage stability stem from load dynamics, constraints in Q, and tap changer operations.

d. Frequency instability (in AC or hybrid MGs): Frequency fluctuations are attributed to imbalances between load and generation, under-frequency load shedding practices, and constraints in P generation.

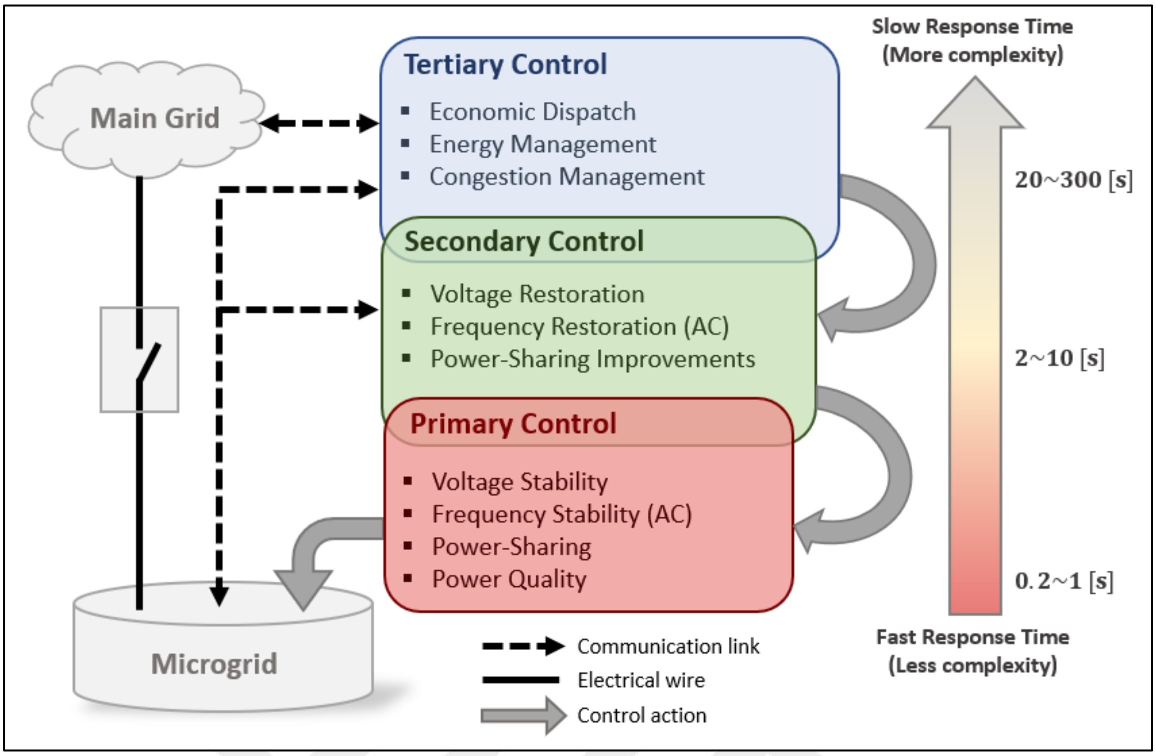

Figure 2.5: Control Layers Utilized for Hierarchical System.

The hierarchical control framework facilitates efficient load distribution, voltage frequency regulation across both operational modes, DG coordination, resynchronization of MG with the main grid, cost-effective operations, and PF management between MG and main grid. This hierarchical structure is divided, as depicted in Figure 2.5, into three levels. The primary loop employs a droop scheme, emulating the behavior of synchronous machines. The SC level is geared towards restoring V-f to the nominal values. The tertiary control loop, often incorporating an EMS, focuses on achieving optimal MG operations and congestion management [61]. The inner control loop is employed to govern voltages and currents at the power converter interfaces within MG [62]. This layer is referred to as the zero-control level and often deploys resonant control, control operating within a synchronous direct-quadrature transformation d-q rotating frame, predictive based control, among others. The hierarchical control is applicable to DC or hybrid MGs by adjusting control objectives within each layer.

2.4.1 Primary Control Layer

PC assumes control over various elements, G, BESS, ESS, DR, RC, and various types of RESs. This layer incorporates essential control hardware and manages the internal Q-V and

P-f control loops within DGs, ensuring stability through the measurement and regulation of local signals [63]. Consequently, it is referred to as 'P/F control'.

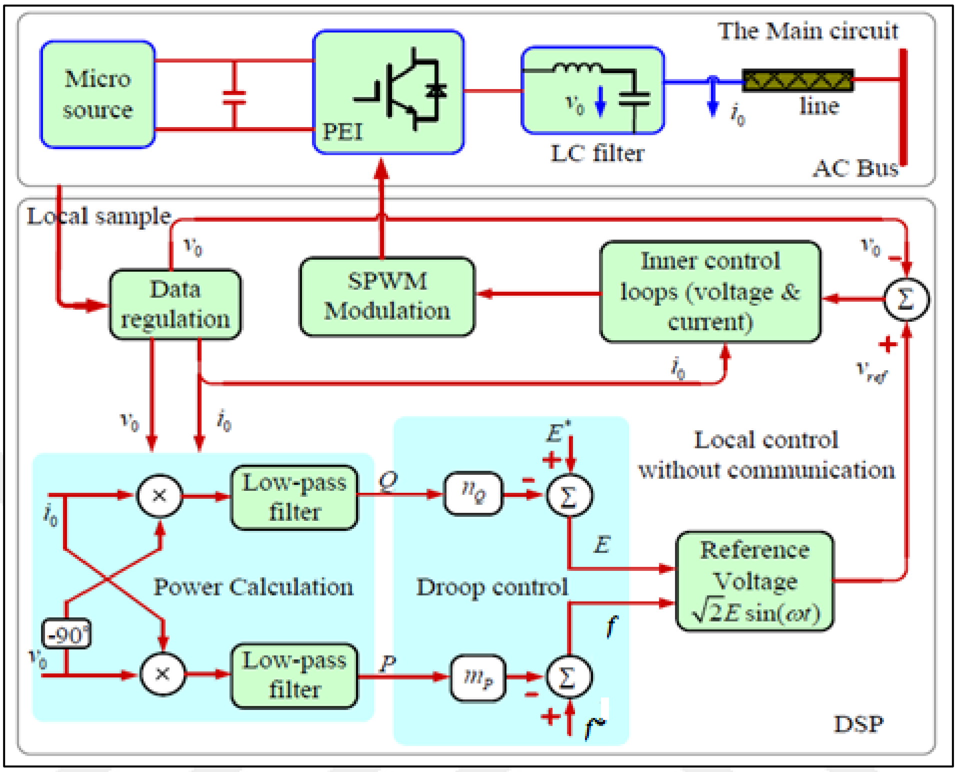

Figure 2.6: V-f Droop Control Structure.

The conventional control mechanisms employ droop to address proportional loads/sources PS and voltage stabilization. There are many modifications added to droop control such us virtual impedance which is introduced at the output of each DG. It's essential to note that this virtual resistance, despite its role in facilitating load sharing, does not represent a physical impedance and hence does not result in power losses. During this phase, the voltage control within each energy source follow the voltage reference established by droop mechanism. 'V_o' and 'so' denote the reference values for inner loops, 'n_q' and 'm_p' represent droop coefficients, where '*V**' signifies MG rated voltage, and '*f**' corresponds to the output frequency at the DG [64]. In a steady-state condition, if distribution line reactance is minimal, the terminal voltage converges to a reference value. The mathematical calculations and process models are presented in Figure 2.6.

Droop entails a decentralized relationship between P and Q, acquired through LCs, and the converter V-f s. These mathematical linear algebraic relationships are expressed as follows [65]:

$$E = E^* - n_q (Q - Q^*) \quad (2.1)$$

$$f = f^* - m_p (P - P^*) \quad (2.2)$$

Where P* and Q* are predefined variables. Integrating droop induces variations in both V-f within MG, as illustrated in Figure. 2.7. The advantage of employing droop control resides in its capacity to enable PS without necessitating a communication link, thereby conferring flexibility and autonomy [66]. Furthermore, in AC MGs, droop curves defined in equations 2.1 and 2.2 facilitate the integration of converter based DERs. Of conventional droop control, several limitations arise:

a. Deviation in both V-f, represented by d from nominal values as depicted in Figure 2.7, is a popular concern. Addressing these imbalances falls under SC duty, a subject to be explored in the ensuing section, in MGs characterized by low inertia and a predominance of converter based DERs, these deviations become more pronounced.

b. The transient response of conventional droop control displays a gradual response, resulting in instability. The level of instability depends on the variations in droop coefficients. The direct relationship between Q and P, influenced by R/X ratio of the lines and DERs within MG.

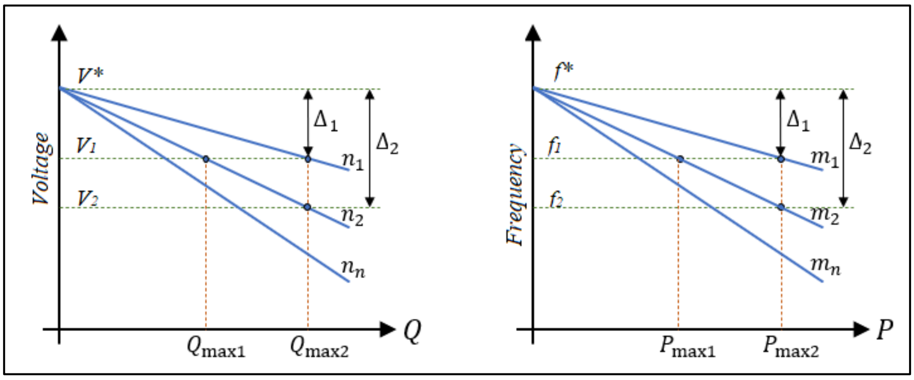

Figure 2.7: Droop Deviations over AC Microgrid Response.

To ameliorate these challenges, droop control integrates improvements through the incorporation of virtual impedance loops. For readers seeking a deeper understanding of this topic, a discussion is found in reference [67]. The subsequent section provides a concise introduction to virtual impedance loops. The total load is distributed among the power sources in an inverse relationship to their respective droop coefficients. The effective management of proportional load sharing is achieved by selecting droop coefficients.

2.4.2 Virtual Impedances

It is employed to modify the dynamic characteristics of power converters through the implementation of lossless software-driven impedances. Integrating virtual impedance control loops has been established to introduce active damping within current control loops. The application of virtual impedances finds extensive use in MGs and distributed generation systems, serving purposes such as enhancing stability, mitigating THD and imbalances, facilitating Fault-Ride Through control, and more [68]. Another notable application of virtual impedances is the decoupling of Q and P outputs from power converters. In conventional AC MGs, droop control equations assume strong inductive characteristics in the lines and impedances connecting DERs to loads. However, this assumption still hold significance in low-voltage MGs. To mitigate this concern, the introduction of a 'virtual inductance' loop is proposed to enforce inductive coupling. Moreover, the concept of virtual impedance remains relevant even when system impedances demonstrate strong inductive characteristics, and inefficient PS among DG converters occurs due to variations in output inductance s [69].

An analogous method is applied to DC MGs to improve P distribution. The use of the virtual impedance loop is illustrated in Figure 2.8. This representation assumes the adoption of the control scheme within the abc reference frame for managing a 4-leg power converter. The figure exhibits nested control loops, where the outer loop regulates the voltage across the LC or LCL power filter capacitor, while the inner loop controls the current's inductance. As explained in [70], virtual impedances are classified into 'inner' and 'outer' categories. In Figure 2.8, the inner virtual resistance is employed for active damping in the power converter topology displayed in Figure 2.8(a). Moreover, the figure displays three outer virtual impedance loops. Among these loops, two utilize both harmful sequence and zero-sequence components of the output current (ii) to enhance negative sequence and neutral current sharing among MG power converters. Finally, an additional outer virtual impedance loop offering virtual inductance to improve RPS. The integration of supplementary loops is feasible for controlling the THD in MGs. In MGs, the main objectives of virtual impedance loops include augmenting the sharing of specific harmonic currents and harmonics-current sharing. This entails introducing an additional term into optimized droop to strike a balance between harmonic-current sharing and preventing high THD of the voltage within MGs [71], in 4-wire systems, the emphasis lies in addressing harmonics, whereas in three phase systems, compensation for the 5th and 7th order harmonics is considered, considering the computational capabilities of the control platform.

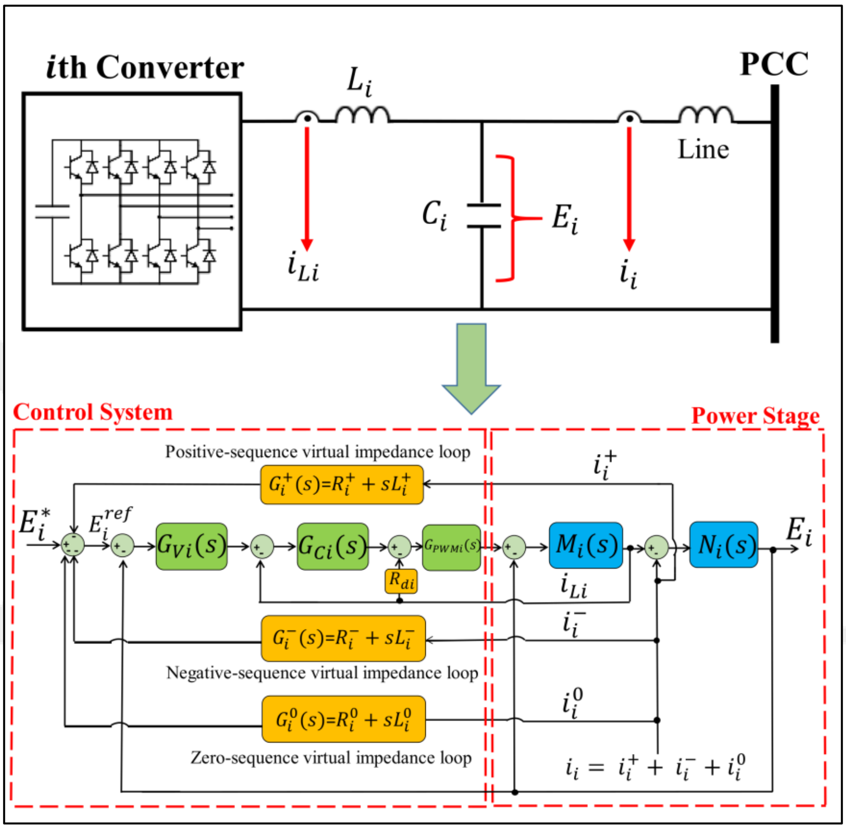

Figure 2.8: Implementation of Virtual Impedances.

One significant challenge associated with the virtual impedance loop implementation relates to the impedances design. This challenge stems from the typical alterations observed in the equivalent DER Thevenin impedance during MG operation. Academic literature suggests the use of adaptive impedance loops to address these variations. These adaptive loops adjust the real-time values of virtual inductances and resistances. For instance, in scenarios where MGs exhibit a low inductive nature, a distributed adaptive approach utilizes optimized droop to fine-tune PC layer settings. This adaptive process involves employing Proportional-Integral (PI) control to modulate virtual resistance values based on Q mismatches among DERs. A similar approach is adopted to correct virtual impedance values. In this case, PI control is employed to regulate local generation deviations, thereby achieving PS among parallel converters within an Uninterruptible Power Source (UPS) modular. Also, many algorithms capable of mitigating drawbacks is designed, such as deviations stemming from decentralized droop control. Subsequent sections discuss distributed strategies involve elements of both PC and SC layers.

2.4.3 Primary Control Simulation

Integrating a remote MG is a common approach for supplying electrical loads in locations that lack connectivity to the main grid. Managing such a low inertia MG presents considerable challenges due to the inability of the main grid to balance load fluctuations. In the illustrative example provided in Appendix Simulink Figure A.1, MG comprises three DGs subsystems interconnected with two PCC buses [72]. MG achieves power equilibrium with fixed loads, alongside the incorporation of a switchable load to implement preplanned load-shedding strategies to attain operational balance. In remote MGs, the instantaneous shedding of loads poses challenges, this example is a high-level EMS.

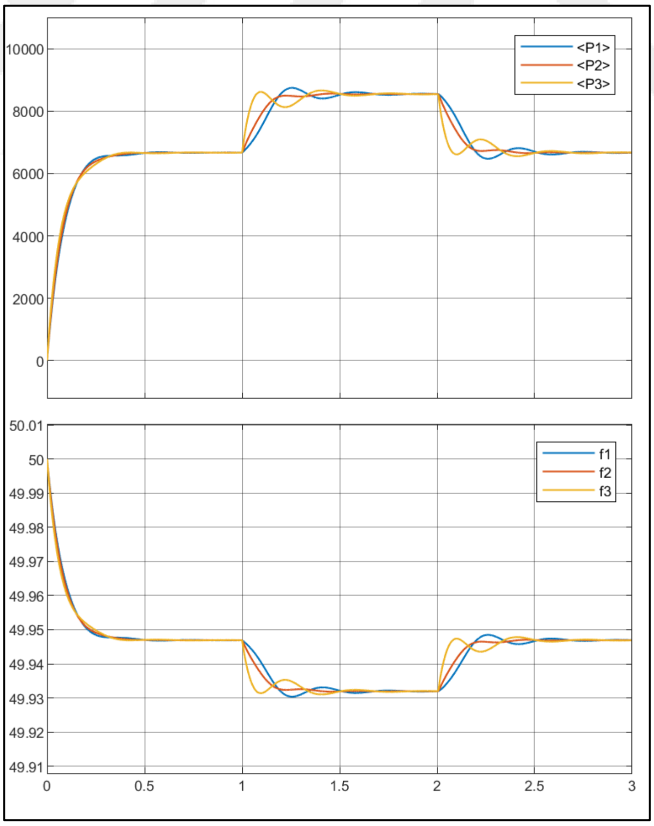

Figure 2.9: Power Sharing Response of Droop-Controlled (3 DGs) MG.

MG voltage and frequency remain close to the nominal values (380 V_{rms} and 60 Hz, respectively) through the application of droop control. Within MG inverter subsystem, an interface with DC source to represent the DC link of common RESs such as PV or ESS. Each subsystem incorporates a droop control for d-q axis reference voltages computing [73]. The voltage control ensures voltage regulation via a PWM inverter. The connected loads consume a cumulative 175 kW power with 0.95 power factor.

Droop coefficients n_q and m_p are set at 2.5%, implying that PCC frequency can vary by 1.5 Hz with a one per-unit change in P injection from a DG. Droop Q/V is set at 2.5%, allowing PCC voltage at PCC buses to fluctuate within 9.5 volts around the nominal 380 V_{rms} with a one per-unit Q change [74]. Figure 2.9 illustrates the variations in (reactive and active) power generation for each DG. These variations are designed to stabilize V-f, during startup and transient responses when a load of 5.8 kW and 200 VAr is introduced between times 1 to 3 seconds. Furthermore, a V-f drop occurs, which is referred to as virtual impedance.

2.4.4 Secondary Control Layer

SC regulates PC reserves, which play a crucial role in balancing load - generation in the short term, during transient periods. It achieves this by restoring the voltage level to its nominal value following any disturbances or modifications of reference values [75]. This SC operates by facilitating PS among DGs configured in parallel through a communication-based approach. Moreover, it compensates for V-f deviations due load variations and local control operations. The mathematical representation of this control strategy is as follows:

$$\text{Voltage Control: } E = E^* - n_q\,(Q - Q^*) + dE_i + dQ_i \tag{2.3}$$

$$\text{Frequency Control: } f = f^* - m_p\,(P - P^*) + d\,f_i \tag{2.4}$$

Here, the *di* values serve as compensatory variables for the D in-droop PC, as depicted in Figure 2.7. While droop ensures desired load sharing, as indicated in Figure 2.10, it also monitors PCC voltage via comparing it to a desired voltage.

SC generates a voltage correction term that is distributed to all sources [76]. In this mathematical model, dE_i represents SC variable for voltage control. The positive gains *Kp* and *Ki* is adjusted to modify system dynamics. $Q_i = Q_j$ signifies the normalized i^{th} DER Q. The equations in the figure contain *dEi* correspond to voltage droop control. *dEi* + *dQi* provides a trade-off between regulating voltage (E_i) and achieving a normalized Q. This trade-off is a well-recognized feature of SC applied to droop-based converters. It is essential to note that all measurements are referenced to a d-q rotating frame oriented at θ. This distributed control is implemented on converters of an isolated MG.

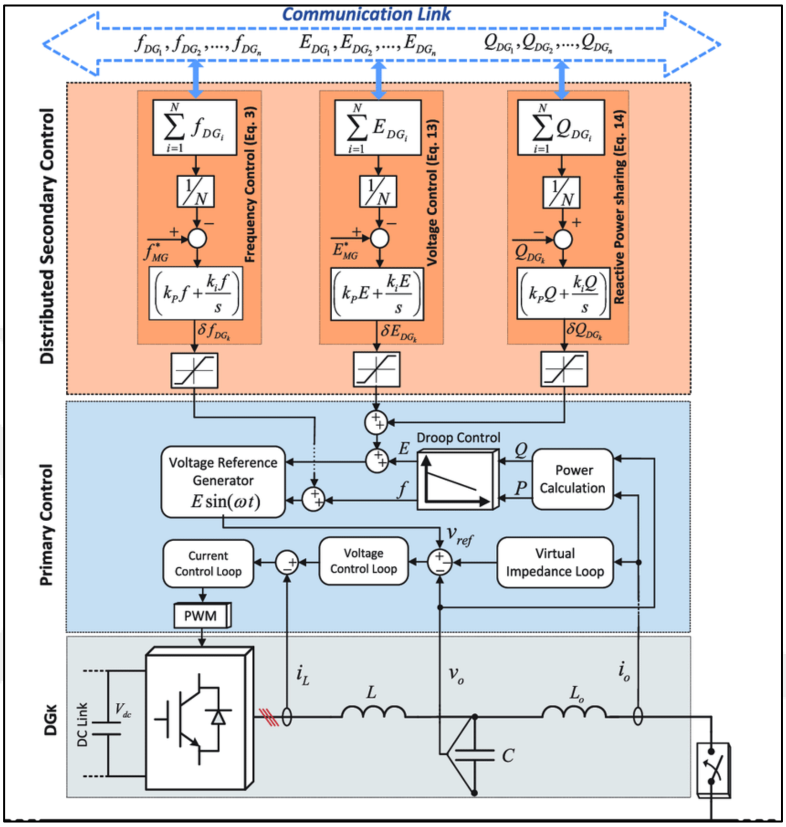

Figure 2.10: AC MGs Distributed SC Control Implementation.

df_i is employed to restore the frequency, where $Kp > 0$ serves as a coefficient governing the velocity of SC, influencing the control's transient response. The variable f represents the frequency, while P_i signifies i^{th} DER active power. SC for frequency control is based on standard droop control with additional SC input df_i. The integral term ensures frequency restoration in steady-state, given that frequency is treated as a global variable (i.e., $fi = f^*$). Furthermore, the condition $df_i = df_j$ must be satisfied for all DERs to ensure that the same value adjusts all droop curves, thereby maintaining P-sharing. The voltage control aims to restore DG voltage while enhancing PS among these units.

2.4.5 Secondary Control Simulation

The sources employ V_{ref} as the reference within droop mechanism. v_o represents voltages across the system, which are utilized in the closed-loop feedback control system to restore all voltages to the rated value of MG. It is important to acknowledge that v_o for MG and V_{ref} is not always align in value, although they are equal.

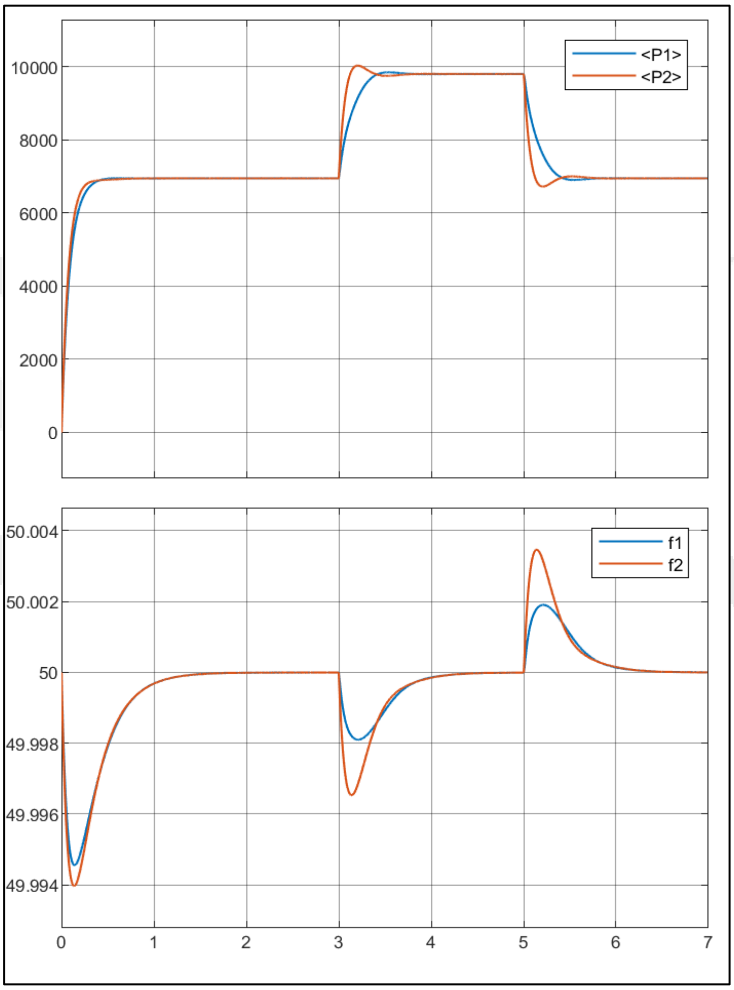

Figure 2.11: P/F Response for SC Control of Microgrids.

In the Simulink diagram presented in Figure A.2 of the appendix section, MG subjected to droop control is modified to incorporate SC under the same load shedding conditions. Figure 2.11 illustrates the PS control achieved by SC system, highlighting its ability to restore frequency responses.

2.4.6 Tertiary Control

It facilitates the supervision activities of MGs. Its role becomes crucial during island mode. Functioning as an MG EMS, it oversees both local and SC within MG [77]. Also, it assumes responsibility for tasks including connection/disconnection (islanding detection) to or from the main grid, protection, and emergency control schemes. In cases where power generation in a MG exceeds the demand, when maximum RESs power absorption is the targeted, excess power is channeled to a high inertia system or the primary AC grid through an inverter. Also, when generated power is not able to fulfil the demand in the main grid and need power from MG. Therefore, a high inertia bidirectional exchange of energy necessitates a control known as tertiary control.

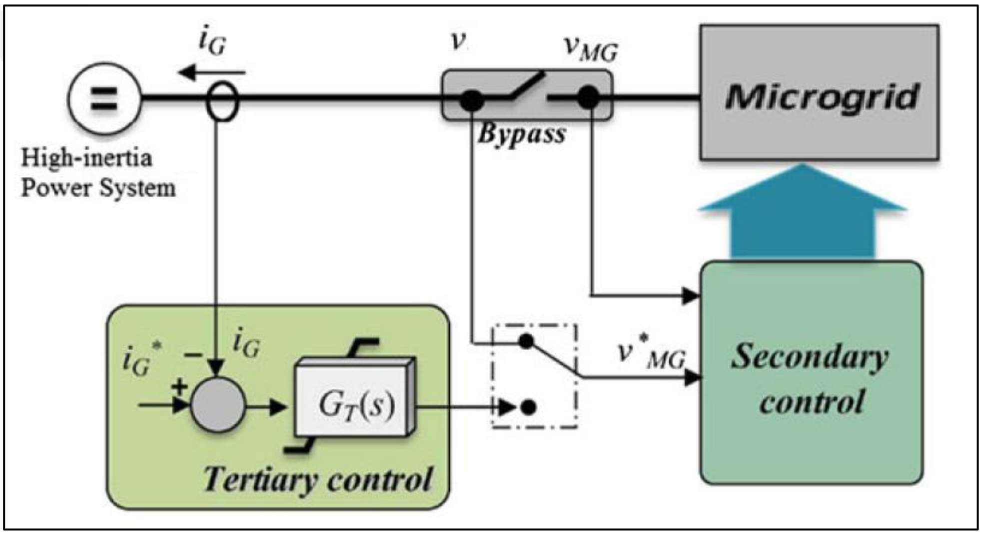

Figure 2.12: Tertiary Control for Grid-Connected MGs.

As depicted in Figure 2.12, the tertiary control assesses PF between the two grids against a reference value of Ig and adjusts MG's reference voltage accordingly [78]. An increase in V_{ref} results in greater power output from MG, and vice versa. Also, global control oversees PF not only within the given MG but also between main grids and MGs, ensuring economic optimal operation. Below are the ongoing research challenges in MG control:

a. Improving closed-loop systems transient response.

b. Addressing power quality issues related to harmonics and imbalance.

c. Strengthening FRT capabilities.

d. Developing unified strategies applicable to both grid-connected and islanded modes.

e. Ensuring a transition of islanded to/from grid connected mode.

2.5 POWER SHARING CONTROL

The PS control allocates the power reference, which includes voltage and current parameters, for each DG connected to the common bus. This allocation aims to ensure adherence to the physical constraints of equipment while meeting the power quality requirements related to V-f regulation. Figure 2.13 illustrates a simplified equivalent model of a distributed system consisting of two parallel converters to supply a single load.

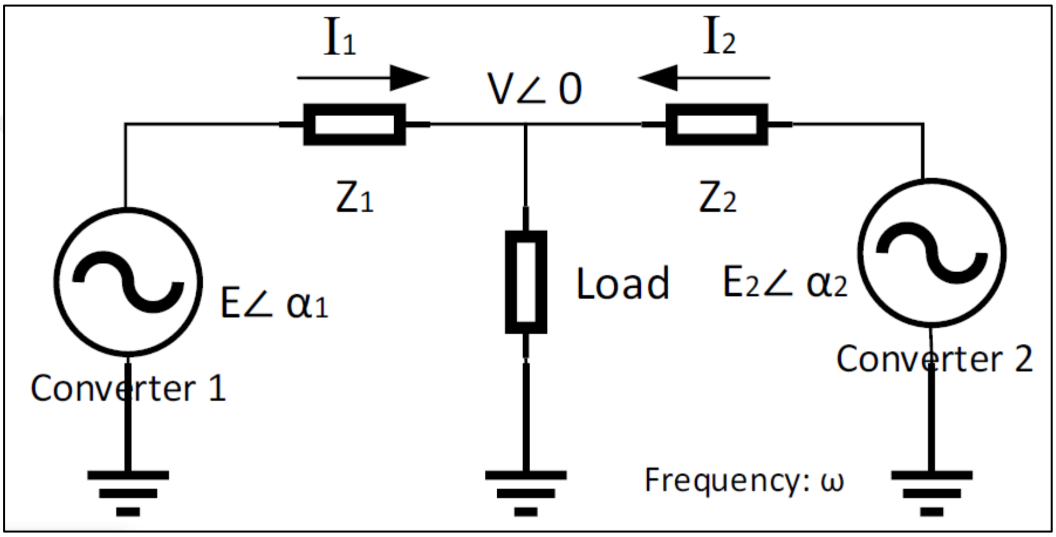

Figure 2.13: Equivalent Model of Two Parallel Inverters Supply a Common Load.

The PS module's primary task is to determine connected the values of current denoted as I_1 and I_2. These values are calculated in such a way that they fulfill the load demand without causing overloading of any of the converters within the system [79]. The PS control approaches classified into master-slave, concentrated, and distributed, based on their communication characteristics. To provide an overview of these control approaches, it is essential to analyze the advantages and limitations of each topology. This analysis, based on relevant criteria, is summarized in Table 2.2. Master-slave is referred to as communication-based control, where the highest capacity generator assumes the role of the master [80]. This master DG is responsible for controlling the voltage at the common bus and managing transient disturbances. In contrast, slave inverters ensure efficient PS among them. However, other techniques employed a current sharing module to measure load current (I_{load}) at PCC bus.

Table 2.2: Comparison of Power Sharing Topologies

Criteria	Topology		
	Master-slave	**Concentrated**	**Distributed**
Preventing SPOF	✗	✗	✓
Considering constraints	✓	✓	✗
Low computational cost	✗	✗	✓
Low communication bandwidth	✗	✗	✓
Transient & accuracy response	✓	✓	✗

Through this module, reference (I_{ref}) current for each DG is determined, while average (I_{ave}) current calculated as I_{load} / N, where N is total DG number in MG. On the other hand, distributed control, known as non-communication approach, necessitates that each DG regulates the voltage by simultaneous PS. Among various PS strategies, adopted distributed control schemes are based on droop characteristics. This approach is favored for its heightened reliability and flexibility, as it facilitates the synchronization of inverters for each DG based on PCC voltage. Thus, the droop control method within distributed control regulates power flow by leveraging sensed current and voltage data at PCC. This method is well-suited for MG environments, given its reliability and adaptability.

2.6 MICROGRIDS CLUSTER CONTROL AND STRUCTURE

Extensive research efforts have been dedicated to the design and management of MGCs. In recent times, MGCs, characterized as interconnected multi-MG, have evolved into flexible networks that involve multiple individual MGs, often in close geographical proximity and linked to electric distribution bus. Efficient energy coordination among these MGs hold the potential to improve overall stability and reliability.

The subject of MGCs has gained required importance in contemporary research, with a primary focus on achieving efficient utilization and distribution of RESs, Distributed Renewable Energy (DRE). This emphasis aligns with the objective of promoting the effective deployment and consumption of DERs [81].

MGCs offer several prominent advantages. Firstly, in both islanded modes and grid-connected, they exhibit favorable economic characteristics.

This is attributed to the ability of DGs within MGs to fulfill their energy requirements with cost-effective renewable sources, thereby reducing reliance on fossil fuel generation. Also, energy transactions occur among geographically proximate MGCs, minimizing energy losses associated with long distance transmission lines. Also, as shown in figure 2.14, there are many similarities between MG and MGC in physical and communication layers. Thus, they align more with the future development trends of smart grids. The increasing deployment of RESs in these MGCs optimizes renewable energy utilization within the distribution network.

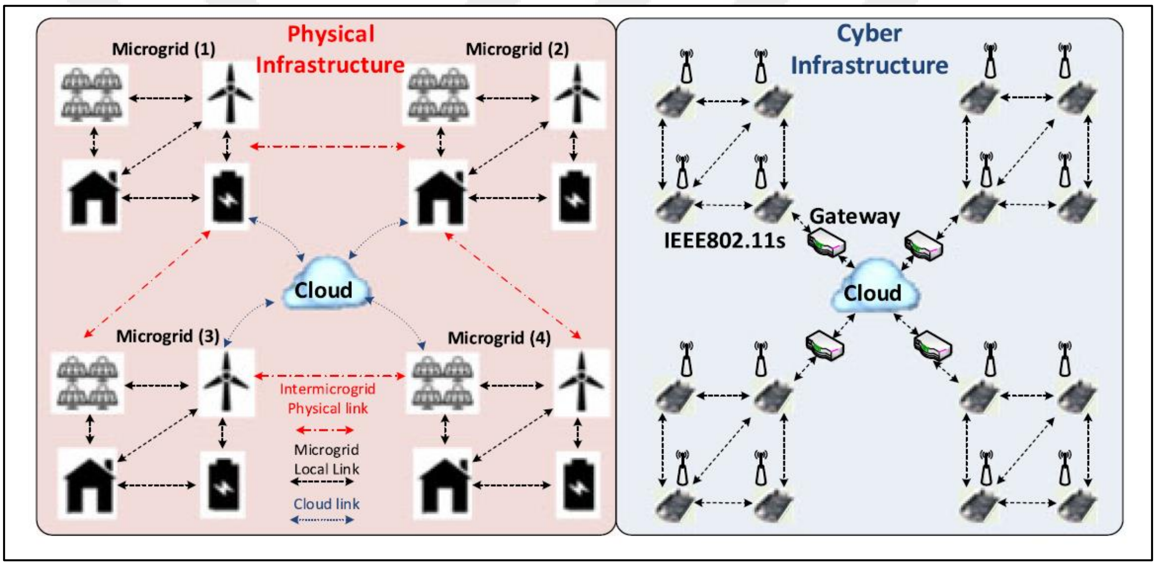

Figure 2.14: MGC Communication and Physical Infrastructure.

Furthermore, MGCs alleviate some of the main grid burden by facilitating energy exchanges among, alleviating distribution lines congestion, and enhancing total reliability of both MGs and the main power grid. Also, a smart distribution system comprising multiple MGs demonstrates a robust self-healing capability [82].

In the event of a fault or natural disaster causing an outage in a geographical area, an MG can isolate from the affected grid sections. Ensuring stable operation by sharing spare power with main grid or other interconnected MGs. DNs are autonomously divided into multiple connected MGs to improve operational efficiency and reliability. MGC can pool their generation capacities and achieve reliability and avoid load curtailments. However, despite these advantages, several challenges persist in achieving stability and reliability in MGCs. First, MGCs can exhibit a high renewable energy penetration, leading to increased intermittent in both temporal and spatial aspects. Effective EM strategies are crucial to mitigate the volatility impact. Second, the interconnected nature of MGCs results in strong coupled energy interactions during PS.

Optimization of one MG's energy schedule can affect others, and as the number of DGs within MGCs increases, the complexity of energy scheduling also grows [83]. Also, MGs and main grids is controlled and operated by different entities with objectives, often prioritizing autonomous MG management and privacy preservation when sharing spare energy. Consequently, optimizing scheduling algorithms can influence energy utilization patterns and buying/selling practices. These challenges underscore the necessity for diverse EMS schemes designed for various scenarios.

2.7 TOPOLOGIES OF MICROGRID CLUSTERS

In MGCs, all DGs are interconnected to enable exchanging and sharing of energy through power lines. Thus, they establish a complex network system comprising multiple MGs characterized by diverse topologies. Furthermore, oversight of PF control and market operations, involving trading energy to the grid to reduce the congestion during energy transfers, is executed by Distributed Network Operator (DNO) [84]. Each MG is equipped with RESs, ESS, various load types. The EMS supervises these components, needs efficient, dependable, and low-latency communication infrastructure. In this regard, the subsequent subsection explores the discussion of the three popular topologies of MGs.

2.7.1 Radial Topology Model

In this configuration, each MG establishes a direct connection with the grid, thereby forming a conventional radial (or star) topology. Every MG links to a bus, facilitating exchange of energy between MGs and the main grid hub bus connection [85]. This configuration is depicted in Figure 2.15, where direct energy trading does not occur among the individual MGs. Figure 2.15 depicts the local energy system MGC, comprising multiple MGs, emphasizing the exchange of information among these MGs and DNO within the tertiary control framework.

These MGs possesses the capacity to adapt to decisions made by DNO and its internal EMS. Energy trading/sharing depend on dedicated power exchange pathways.

If one MG cannot meet its load demand, it can obtain energy from the main grid via the exchange connection [86]. However, an MG with spare energy can sell its excessive power to the main grid using the same connection. Thus, managing energy in MGC structured in this way require assessing PS capability of ensuring safe energy exchange with the main grid. This can reduce the congestion in main grid power distribution lines and enhance overall grid reliability [87].

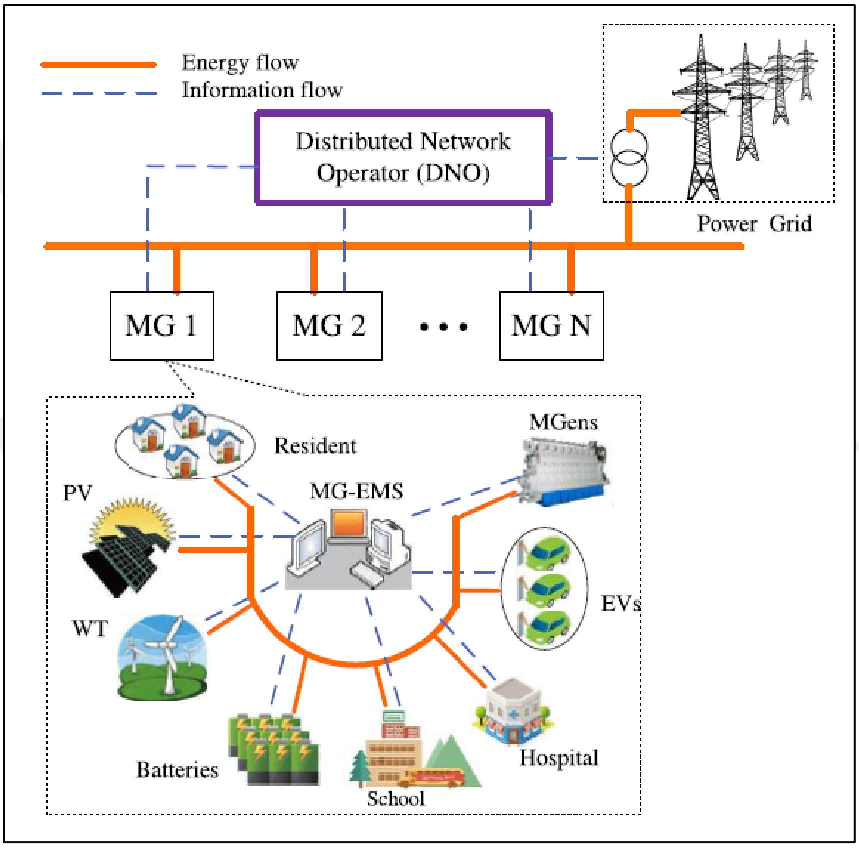

Figure 2.15: Radial Topology MGCs Architecture.

2.7.2 Daisy-Chain Topology

In this configuration, each MGs is connected to a main grid bas and other MGs, enabling the exchange of energy with the main grid and neighbor MGs these designated buses [88]. As depicted in Figure 2.16, it illustrates DNO and MG-EMS controlling the energy exchange and trading on the transmission lines.

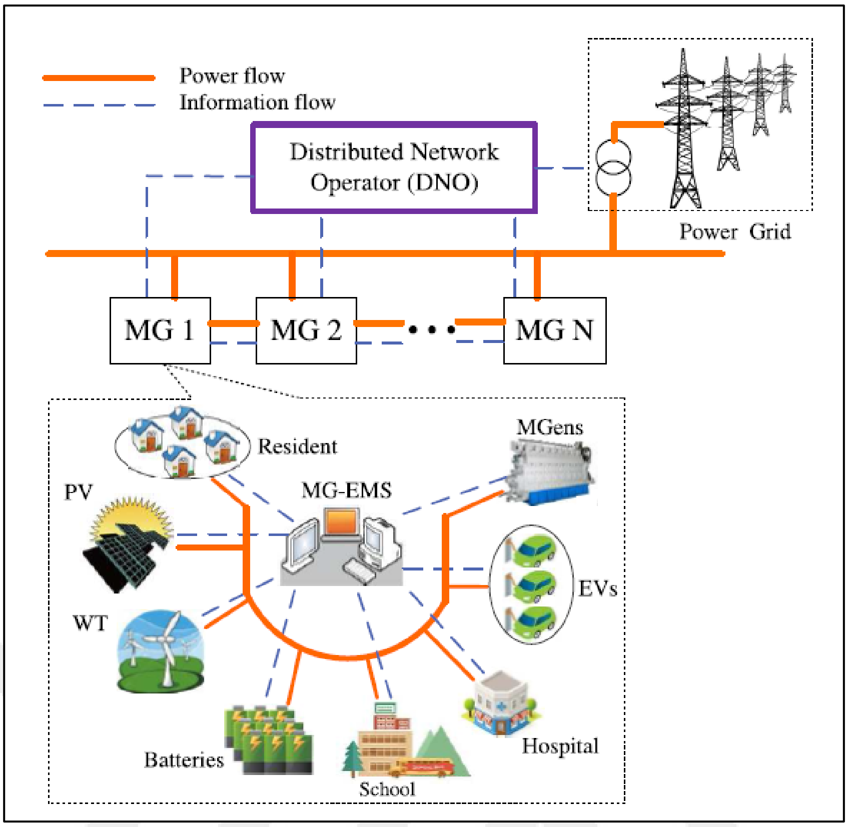

Figure 2.16: Daisy-Chain Topology MGCs Architecture.

2.7.3 Mesh Topology

Illustrated in Figure 2.17, MGCs is built with mesh topology interconnection through a communication network and power transmission lines [89]. Within this configuration, it is common for MGs to incorporate many types of RESs. The collaboration of MGs within this structure facilitates efficient exchange of both energy and information, improving the operational efficiency and cost-effectiveness.

Nevertheless, this structure surpasses the complexity of other topologies, leading to complex energy coordination and collaboration. The scheduling of each interconnected MG depends on its local energy supply and demand dynamics and the behavior of other MGs within this MGC network [90]. This leads to broadening the search space for identifying the optimal EMS solution. Thus, the design of the EMS algorithm becomes more complex and challenging.

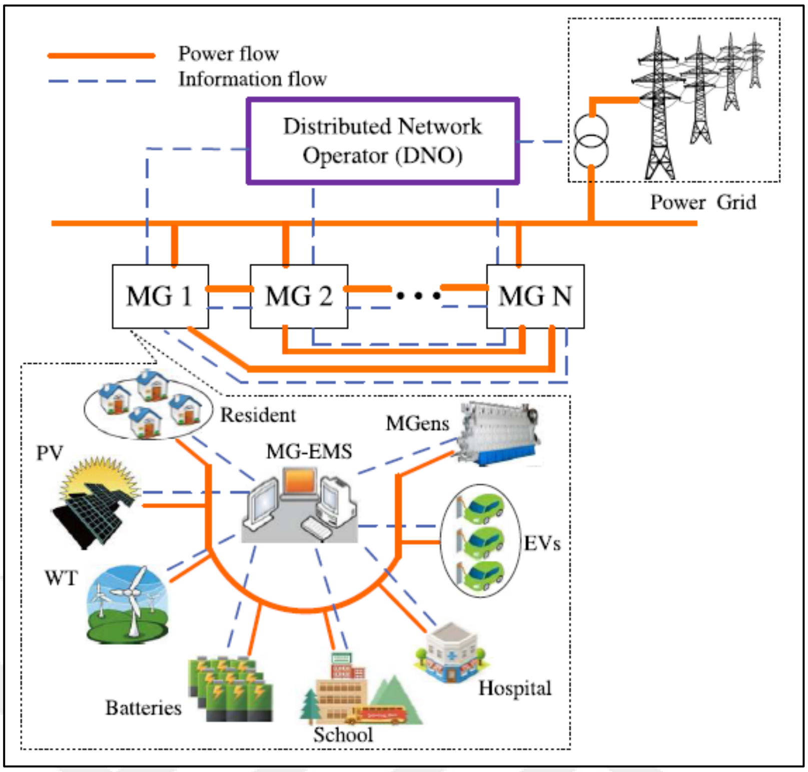

Figure 2.17: Mesh Topology MGCs Architecture.

2.8 ENERGY MANAGEMENT IN MICROGRIDS

The EM plays a pivotal role in MGs operation. The functions of an EM involve the allocation of generation share to each energy source identity in the system whether it is a DG in MG or a MG in MGC.

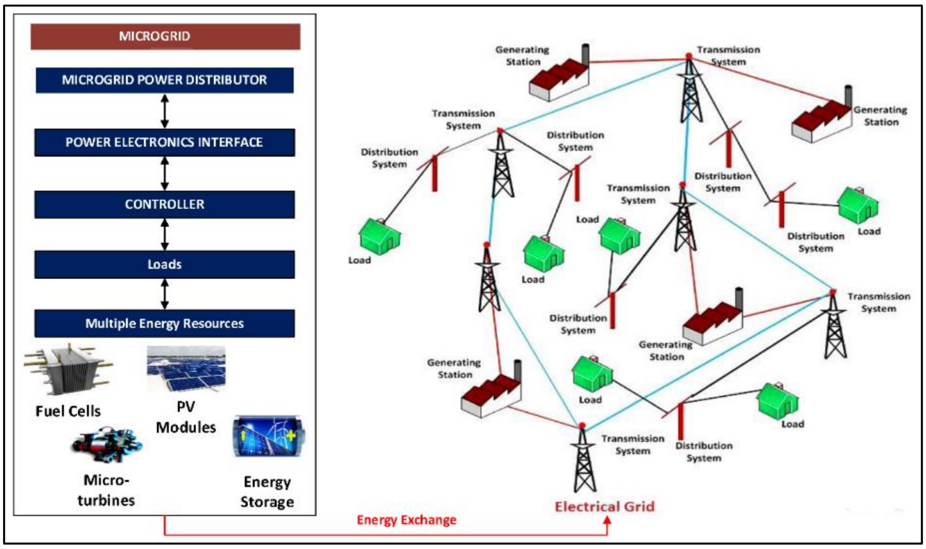

Figure 2.18: Energy Management in Microgrids.

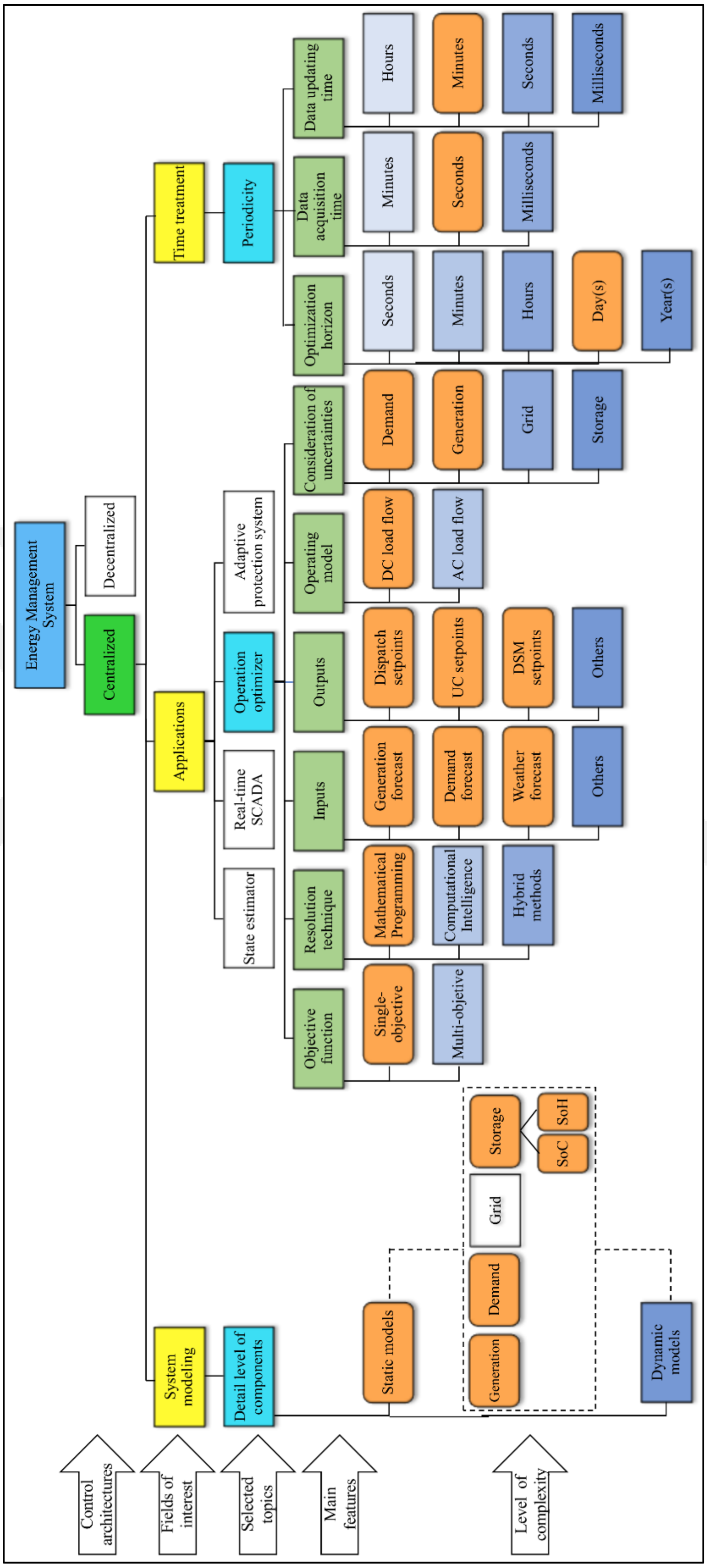

Figure 2.19: Energy Management Methods.

As shown in Figure 2.18, it involves complicated steps used in monitoring controllable loads to regulate the supply-demand balance, thereby facilitating spare energy sharing [91]. To enhance the resilience and cost-effectiveness of MG operation, a novel approaches of energy cooperation among MGs have emerged aim to reduce reliance on fueled generators or unreliable RES, which are constrained by limited capacity and high operational costs. Thus, EMS coordination is compounded by the complex uncertainties stemming from the nature of generation, loads, and the energy market. These variables often exhibit strong correlations, adding layers of complexity to EMSs interactions [92]. The energy trading must engage in external interactions with other MGs while managing local energy supply and demand. As shown in Figure 2.19, it involves complicated methods involve operating cost minimization, enhancing user satisfaction, optimizing RES utilization, minimizing energy transmission losses, and maximizing environmental benefits.

2.8.1 Operating Cost

MGs control must facilitate the exchange of energy both with the main grid and among interconnected MGs in MGC, thereby offering reduced operational costs process. Several strategies are employed to achieve the objective of cost minimization [93]:

a. Maximizing Utilization of RESs: It involves integrating RESs within MGs. By harnessing these sustainable resources, MGs aim to reduce the dependence on conventional energy sources, which entail higher costs.

b. Strategic Energy Transactions: It entails selling spare energy to the grid during periods of high pricing and purchasing energy from the grid when prices are lower. This approach aims to benefit from market dynamics to the advantage of MGs.

c. Cost Reduction in Fueled Generators: It focuses on reducing the demand and costs of fueled generators. These generators often involve substantial operational expenses, thereby lowering costs.

Also, there are other strategies to provide cost-effective operation and enhanced sustainability. These strategies involve optimizing RESs integration, energy trading, and reducing the expenses linked to fuel.

2.8.2 Customer Satisfaction

Assessing customer satisfaction with energy allocation is a multifaceted process, it arises due to the diverse nature of customers, each having different satisfaction levels confronted with poor demand and/or supply conditions [94]. Therefore, several models are developed to predict future supply and demand. The user's satisfaction relies on how much his demands are met; high satisfaction corresponds to demand satisfaction, while low satisfaction indicates unmet demands. Thus, categorizing energy loads into types is a common strategy, such as dispatchable, non-dispatchable, flexible, and non-flexible loads.

The dispatchable loads require rigid demands to be satisfied (e.g., lighting), whereas non-dispatchable flexible demands loads can be delayed to some extent. Satisfaction level concerning this categorizing is inversely related to the gap between allocated power and degree of delay. Thus, scheduling algorithms is proposed to prioritize loads based on specific demand and supply conditions [95].

2.8.3 High Penetration of RESs Tolerance

MGs optimizes integrating RESs, achieved through two ways. The first approach entails exchanging excess energy to meet the demands of other high-consumption MGs. The second approach for enhancing more RESs integrating by monitoring the DGs power supply and shaping the load profile [96].

2.8.4 Transmission Loss

MG-MG, MG-MGC, and MG-grid energy exchange involves two forms of transmission losses. The first category, the losses occurring within MGs, is covered by research works concentrated on mitigating such losses [97].

The second category is main grid transmission lines losses. These losses are more serious since MGs are low-voltage systems, while the main grid operates at high voltage levels. Thus, energy trade on grid lines (MG-MGC, and MG-grid) results in substantial losses. Mitigating these losses can facilitate more energy to be transmitted.

2.8.5 System Flexibility, Stability, and Environmental Benefits

Flexibility is assessed through energy coordination, while stability is often enhanced by monitoring and avoiding generation sudden failures or blackouts events [98]. Also, the environmental measure involves greenhouse gas emissions evaluation and reduction. The existing optimization framework of MG Management, a popular approach, involves multi-objective optimization. Thus, the optimization of an objective function must combine these aspects in response to actual demand.

2.9 TIMESCALE OF OPTIMIZATION

This parameter plays important for ensuring efficient system operation. There are two utilized timescales for optimizing MGs [99]. These timescales for decision-making and adaptation processes in MGs are required as operational and response evaluation factor. It is integral to total response and stability of MGs, as it impacts their ability to respond to dynamic changes and disturbances.

2.9.1 Off-Line Optimization

This energy scheduling and MG planning involve making decisions and adaptations in advance, referred to as day-ahead scheduling depending on relevant forecast information, including data on RESs, market prices, controllable load known in advance. Thus, EMSs can calculate optimal schedules for all the sub-systems within MG [100].

However, this method lacks consideration for future uncertainties of MGs. Thus, alternative approaches such as Monte Carlo leverage uncertainties probability characteristics. It employs techniques, simulations, and scene reduction to maximize the possibility of different solutions under uncertain conditions. This optimization method is employed to determine DERs optimal allocation [101].

2.9.2 Real-Time Optimization

It is day-ahead optimization is a valuable approach for achieving the global optimum power scheduling. However, its effectiveness is hindered by the inevitable prediction errors, as actual values may deviate from predicted values due to uncertainties in DERs, making EM challenging.

Thus, real-time optimization (RTO), as shown in Figure 2.20, used in energy scheduling to mitigate uncertainties is a strategy that aims to schedule external energy trading between the main grid and MGs while maintaining internal operations [102].

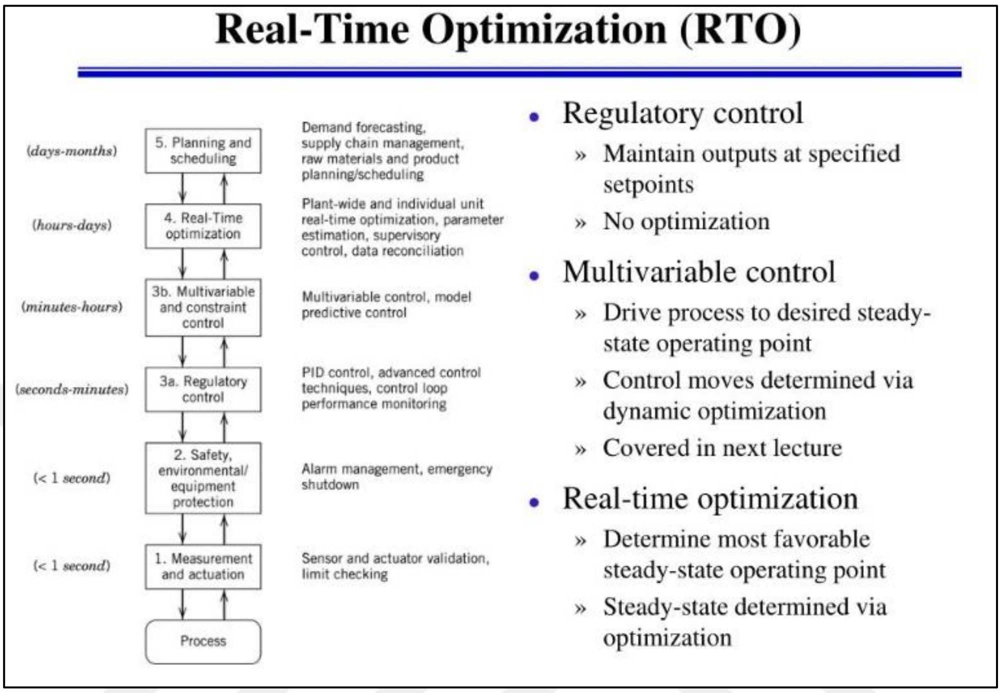

Figure 2.20: Real Time Optimization Requirements in Microgrids

2.9.3 Hybrid Optimization

While real-time optimization is crucial, offline optimization can be used to assess the online optimization algorithms convergence since it is accurate when dealing with single MGs. In scenarios where energy interactions between MGs is separated, the offline optimization is decomposed into sub-optimization [103]. This enables the development of distributed energy optimization algorithms, reducing computational complexity.

2.10 SCHEDULING OPTIMIZATION

2.10.1 Centralized Energy Management

The centralized EMS control in MGs is important in optimizing EM. It collects detailed information from each individual MGs and market data to execute optimization algorithms. While this centralized approach ensures coordination, it involve many drawbacks [104].

a. Higher communication and computation requirements: Centralized control requires extensive communication between MGs components and the central control, which can lead to increased communication and computation demands.

b. Privacy concerns: Users have reservations about sharing their information with other parties. However, information sharing is necessary for the centralized model to function.

c. Single Point of Failure (SPOF): MG relies on one controller functioning as central control. If it fails, the entire EMS can be compromised.

Thus, centralized EMS are rare, there is a growing interest in decentralized methods that can enhance MG resilience, reduce communication overhead, and address privacy concerns.

2.10.2 DERs Management

Centralized EMS methods empower individual MGs to make optimal energy distribution decisions. This approach offers many advantages [105]:

a. Lower Information Exchange: Distributed methods enable each MG to make decisions based on local information, reducing extensive information exchange.

b. Lower Computational Complexity: Individual MG optimization needs lower computational complexity compared to centralized systems.

Many EMS techniques are adopted for large scale DERs of multiple participants [106]. Thus, various other strategies are used for DERs management in MGs, including decision-making, game theory, alternating direction, search metaheuristic algorithms, among others.

2.11 OPERATION CONTROL MECHANISIMS

The grid-tied MGs, a complex interactions control is required, including energy sharing, trading, and competition. Thus, a distributed structure autonomous EMS employs diverse strategies and is crucial ensuring stability, efficiency, and optimal PS.

These techniques are vital for RESs integration and maintaining a reliable supply. Key techniques are used for EMS optimization in such networked MGs include the following [107]:

a. Coordination of DERs: Coordinating MGs DERs and loads is essential for efficient EM.

b. Energy Trading: It is a fundamental enabling trading within a MG, among MGs in MGC, and with the main grid. This needs advanced trading algorithms and policies.

c. Flexible Scheduling: DERs and flexible loads must be scheduled to balance supply-demand.

d. Blockchain for Transactive Energy: Blockchain technology is used in EM to ensure secure energy transactions.

e. Metaheuristic Algorithms: Employed in optimal power dispatch, considering economic and technical constraints in MGs.

f. Peer-to-Peer Energy Trading: MGs incorporate peer-to-peer trading to allow generation units at costumer sides to exchange energy in a governed way.

g. Harmony Search Algorithms: Utilized for managing diverse components in MGs, including DERs, ESSs, electric vehicles (EV), and flexible loads.

These methods form the foundation of distributed control in MGs, ensuring high integration of RESs, efficient PS, and robust stability in various operating conditions [108]. This provides reliable energy systems to cope with growing energy demands and environmental concerns, allowing networked MGs to trade, share, optimize their DERs, and minimize the dependence on centralized control. In the subsequent subsections, many optimization schemes are discussed.

2.11.1 Dual Decomposition Energy Trading

Dual Decomposition optimization technique is utilized scheduling both renewable and non-renewable sources depending on their individual objectives, constraints, and governing policies [109]. To ensure the protection of user privacy and the robust security of grid operations, it limits the information exchange between the DNO and MGs while maintaining optimal scheduling fulfills security and privacy requisites. Furthermore, the dual decomposition extends enables distributed parallel processing to reach optimal EM for multi-entity distributed systems.

During the operational phase, an MG's pricing structure involves the operational expenses of its DGs, along with the expenses incurred from buying energy from neighboring MGs and the grid. Moreover, the MG revenue is aggregated from energy sales to other MGs and grid. However, trading energy is complicated with variables and constraints. In scenarios where objectives remain separable, constraints become challenging problems. The dual decomposition algorithms emerge as a viable for untangling these challenges. The only shared information requirement from each MG is the price. In autonomous interconnected MGs, aligning with the user privacy, the user must mandates sharing information of surging demand.

2.11.2 Game Theory Energy Trading

As shown in figure 2.21, this theory is applicable to various applications. In MG, in serves the effective collaboration among MGs reduces the operational cost. However, each MG is driven by the objective of maximizing its individual profit. This dynamic leads to the emergence of shared conflicts and interests in MGCs, when MGs engage in the exchange of spare energy [110].

However, each MG's decision-making process relies upon its unique capabilities. This presents a challenge since MGs must make choices that are collectively and individually advantageous, considering the competitive nature of this issue. To address these challenges, game theory emerges as an instrument for devising cooperative control strategy in interconnected MGs.

Scholars often employ both cooperative and non-cooperative game theory paradigms to tackle such multifaceted issues, to ensure that each MG benefits from collaboration rather than isolation. Under cooperative framework, MGs can optimize their operations for mutual gain. Furthermore, the potential for additional benefits within this cooperative framework has led to the development of diverse coalitional game theory-based algorithms designed to meet the MGs requirements to facilitate fair energy trading among MGs. Therefore, Nash bargaining-based incentive mechanism has been proposed. This mechanism involves formulating a Nash bargaining problem to improve MGs response based on collective benefit respecting energy exchange constraints with the other MGs and grid [111].

In contrast, non-cooperative game theory assigns incentives to each participant without binding agreements. In this scenario, multiple decision-making entities try to maximize their individual benefits. Nash Equilibrium (NE) controls MG buying competition with varying demands. NE is applicable when all MGs participate in energy trading. To achieve efficient energy sharing, each MG adopts a priority factor within NE strategy, allowing each buyer MG to compete in the energy market using market operator. Another application of non-cooperative theory in electrical energy markets is Stackelberg game, [112].

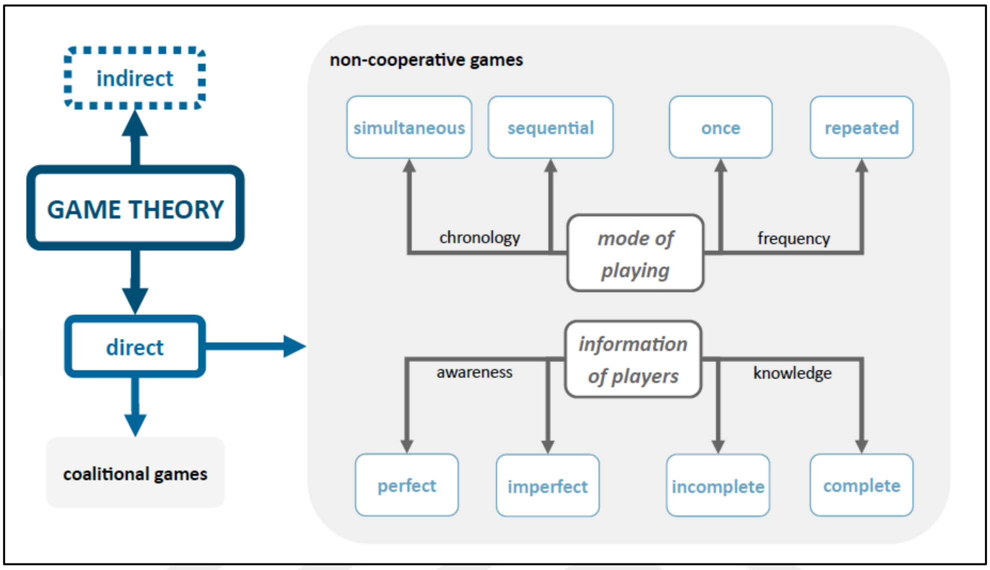

Figure 2.21: Game Theory for Various Applications.

It represents a two-level distributed EMS, where selling MGs act as the leaders of the competition, while buyer MGs take a follower role. Energy allocation for each buyer MG depends on their bids. Also, to further encourage energy trading, consumer-side rewards concept is introduced, promoting energy selling within Stackelberg game framework. In summary, game theory, involving both cooperative and non-cooperative paradigms, serves as a robust framework for addressing the complex energy trading optimization within interconnected MGs to ensure cost savings and enhancing overall efficiency of connected MGs.

2.11.3 Averaging-Based Generation Control

Averaging-Based algorithms compute average values from multiple energy sources in MG promoting uniform load distribution. Thus, they prevent overloading a specific source. A balanced load distribution enhances the response of the entire system and facilitates smoother energy distribution. Averaging-Based algorithms offering sophisticated control to balance energy loads and harness the average values from various energy sources within a MG, as shown in figure 2.22. to promote uniform load distribution [113].

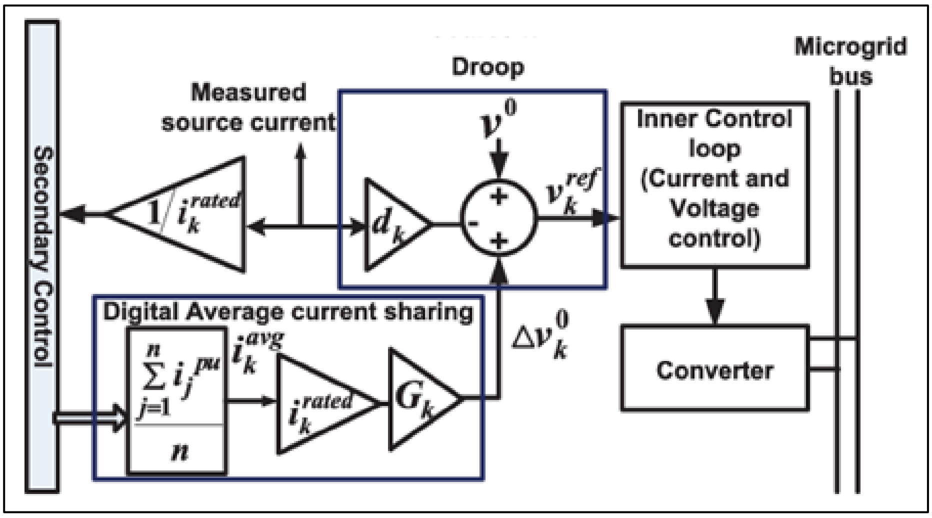

Figure 2.22: Distributed Control of MG with Digital Average Power Sharing

When specific sources bear excessive loads, it not only risk their individual functionality but also poses a risk to the entire MG's stability. These sources become more susceptible to a decrease in their operational lifespan causing inefficiencies and, in worst-case scenarios, system failures. By ensuring each RES operates within its optimal range to handle varying demands with dynamic adaptability in MGs. Furthermore, in the broader view of sustainable EM, Averaging-Based Control aligns with the principles of green technology providing prolonged lifespan of generation units, results in reduced maintenance requirements and lower environmental impacts.

2.11.4 Consensus-Based Generation Control

Consensus control facilitate collaborative decision-making among MG generation and load units. In islanded MGs, centralized control is necessary due to communication constraints. MG components reach a mutual agreement on energy distribution, leading to stable and efficient PS. This approach enhances MG operation by distributed control that elaborates on three approaches [115]. These involve cooperative control, rooted in consensus theory within distributed optimization. Consensus control is often categorized as part of decomposition based techniques, entails the exchange of information among units to resolve localized challenges. Also, there is multi agent control, characterized by autonomous agents executing commands based on local information and information from their neighbors integrating ML techniques. The collaboration within consensus control is represented by asymptotic consensus protocols. These protocols define cooperation and contribute to enhancing convergence speed and stability. The most popular protocols rely upon the dynamic model with first and second order linear models. Moreover, there are various consensus protocols, including delay-robust consensus, second-order consensus, event-triggered consensus, adaptive consensus, consensus with constraints, finite-time consensus, linear consensus protocol, non-linear consensus, and heterogeneous consensus [116], as presented in Table 2.3.

Table 2.3: Types of Consensus Protocols.

Algorithm	Features	Purposes
Linear	Linear systems exhibit the typical advantages and characteristics. This includes adherence to the superposition principle, being describable by linear differential equations, and being amenable to analysis and design using linear control tools. However, when linear systems are applied to non-linear systems [117].	PS Economic dispatch Energy storage
Finite-Time	Systems designed with finite-time convergence possess the potential for quicker dynamic response compared to systems relying on linear consensus. Also, they exhibit good disturbance rejection capabilities [118].	PS Energy storage
Other non-linear	Robust protocols rely on sliding control algorithms. These protocols are claimed to offer increased reliability in modeling disturbances and uncertainties with reduced chattering compared to protocols based on finite-time [119].	PS
Heterogeneous	Agents with varying dynamics are considered. In MG, both first- and second-order consensus protocol agents are utilized. These consensus protocols are designed to ensure synchronization even when the agent dynamics differ. This approach allows for effective coordination and control in systems where the components exhibit diverse behaviors and characteristics [120].	PS

2.11.5 Fractional-Order Demand Control

Fractional-order control (FOC) provide flexibility in MG utilizing fractional calculus to adjust the response to varying energy demands. Their ability to handle fractional derivatives and integrals enhances energy balance. Precision is crucial in MGs where rapid adjustments are needed to accommodate fluctuating RESs generation [121]. FOC represents a paradigm move towards complex control systems, incorporating derivatives and integrals of non-integer orders, as shown in figure 2.23. This approach provides unparalleled precision and adaptability in modern control theory enabling precise modeling and control of complex systems with fractional dynamics.

Many practical applications exhibit behaviors that cannot be captured by traditional integer-order models such as robotics, aerospace, and biological systems, where even minor deviations cause significant consequences. The adaptability to diverse systems is vital since traditional control struggles with RESs where energy fluctuate rapidly, demanding control that can adjust to varying conditions that change behavior over time [122]. FOC fractional derivatives excel in adapting to such variables of nonlinear systems. In MGs where safety and reliability are required, FOC ensures sources and loads operate within desired parameters under diverse conditions by modeling minimum energy transfer processes, where minimizing energy is a top priority.

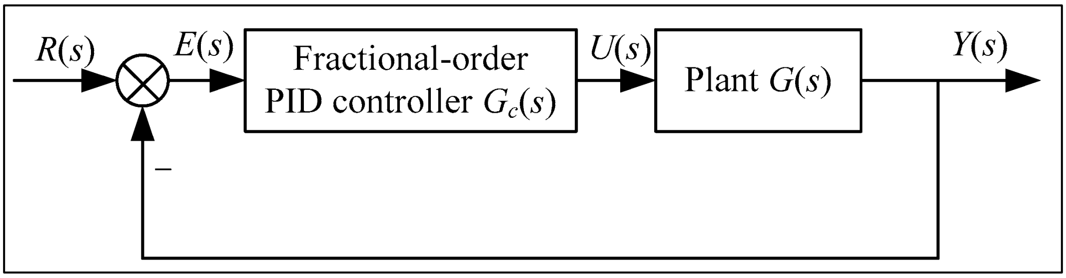

Figure 2.23: Block Diagram of Closed Loop FOPID Control.

2.11.6 Optimization Algorithms

Many algorithms, as shown in Figure 2.24, consider various parameters in MGs such as energy demand, supply, storage capacities, and network constraints. By determining the best configuration for MG operation, they ensure optimal PS, making MG responsive to changing energy dynamics and demand patterns. Optimization algorithms play a role in islanded MGs operation where localized energy systems comprising DERs resources.

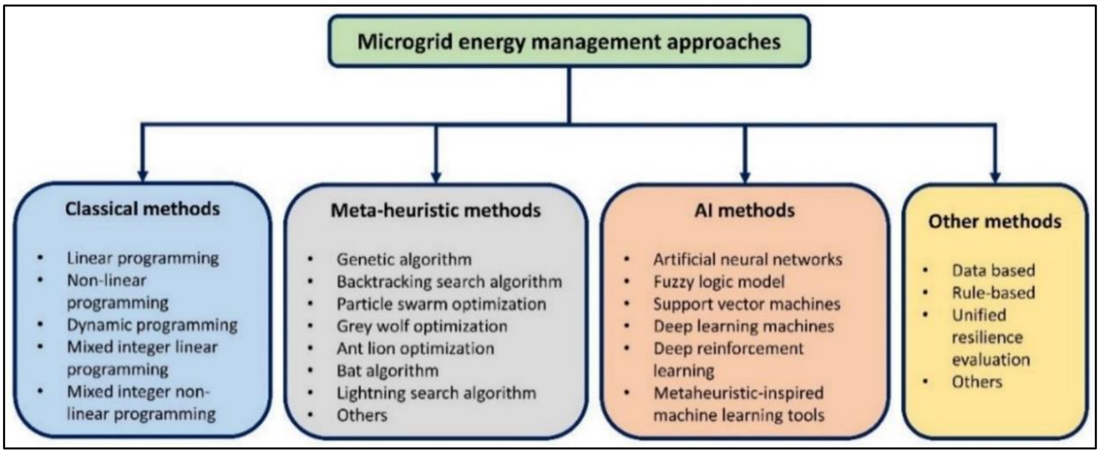

Figure 2.24: Energy Management Methods in Microgrids.

Many AI algorithms are used in decentralized decision-making control in MGs. These methods enable individual components within MG to optimize their operations using ML techniques, such as neural networks and support vector machines to predict energy demand patterns with high accuracy. These predictions enable better EM, ensuring MG is prepared for anticipated demand fluctuations. Also, these algorithms facilitate intelligent load shedding strategies during peak demand periods or grid failures, prioritizing critical loads and shedding non-essential loads [123].

Adaptive algorithms analyze real-time data to make decisions, ensuring essential services remain operational even during challenging scenarios. In ESS control, these algorithms contribute to finding the optimal charging and discharging cycles, maximizing battery lifespan and efficiency. MGs can store excess energy during periods of low demand and utilize it during peak times. Also, these algorithms facilitate more integration of RESs by adjusting energy generation based on weather forecasts and grid demand, ensuring a balanced and sustainable energy supply. By more RESs integration, MGs reduce reliance on traditional fossil fuels, contributing to environmental sustainability [124].

2.11.7 Optimized Droop Control

Traditional droop control methods experienced many modifications, integrating advanced algorithms. These algorithms compensate for drawbacks in droop control. By improving load sharing accuracy and stability, optimized droop control methods enhance the efficiency of MGs. Optimized droop control has emerged as a base in EM strategies. New droop control methods leverage cutting-edge algorithms using adaptive control theory and artificial intelligence to enable dynamic adjustments, ensuring precise load sharing among MG components during fluctuating demand and compensating for the MGs nonlinearities [125]. Traditional droop control methods, while fundamental, exhibit limitations such as inaccuracies in PS and vulnerability to disturbances. Thus, optimized droop control techniques are designed to address these drawbacks, incorporating real-time feedback mechanisms and predictive modeling to mitigate voltage drops and frequency fluctuations during rapid load changes. By adjusting parameters based on real-time data, these techniques ensure that each DG receives an optimal share of the load. This enhanced accuracy prevents overloading of specific DG within MG. Nowadays many modified droop approaches including the proposed work of this thesis pave the way for efficient, stable, and reliable MGs [126].

2.11.8 Other Strategies

Many algorithms such as Alternating Direction Method of Multipliers (ADMM) is invented to achieve enhanced distributed controlled MGs. ADMM is utilized to facilitate real-time EM, eliminating the need for forecast data [127]. Lyapunov optimization is introduced in modified version of ADMM, it demonstrates commendable convergence in attaining optimal power schedules, PF, and PS among MGs connected to main grid. This coordination is also developed by using an Interactive Game Matrix (IGM) using a hierarchical genetic modified algorithm [128]. Another prominent algorithm in MG is distributed adjustable robust optimal scheduling algorithm (DAROSA). DAROSA is selected to minimize total cost within MGs such as generators fuel cost, ESS degradation cost, net energy grid trading cost, and MGs energy trade cost.

2.12 COMMUNICATION LAYER

To ensure effective control and operation of an MG, each DG must be updated with information regarding overall MG's operational state [129]. This involves the real-time measurement of P, Q, V, and f at all nodes of MG. Also, loads, DGs, and ESSs information must be shared in the MG control.

Figure 2.25 provides simplified illustrations of the data communication layer. Monitoring frequency, voltage, and power at specific points within MG serves as vital signals for MG's control systems [130].

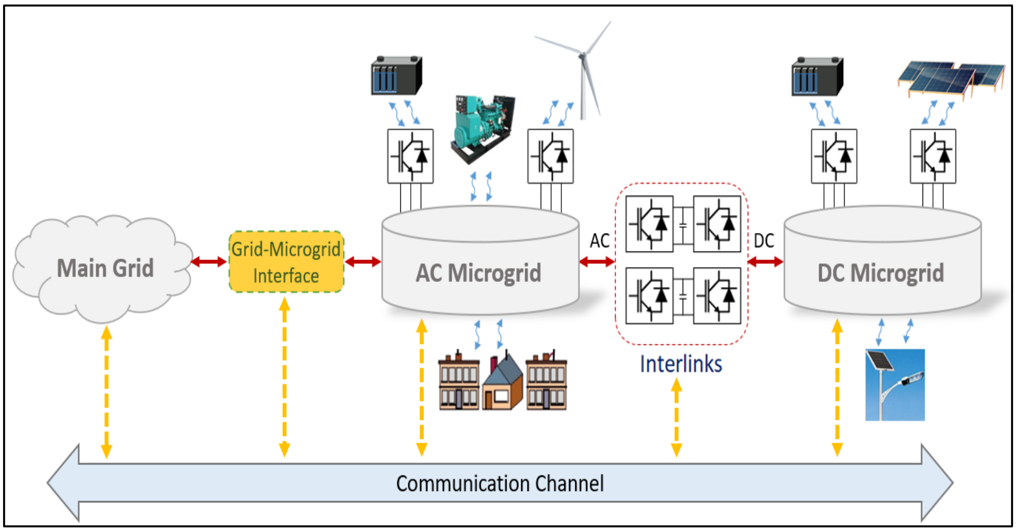

Figure 2.25: Data Communication Layer in MGs.

Also, instantaneous voltage at DG and PCC bus are essential for synchronizing DGs units with MGs and MG with the main grid. Advanced control involves the automation of MGs through sensor-based monitoring, data analysis, using control schemes able to give control intelligent commands to MG nodes. All these require efficient communication infrastructure for commands and data exchange. Communication technologies in MGs are divided into wired (e.g., ProfiBus, ModBus, line communication, and Ethernet) and wireless (e.g., Wi-Fi, Zig-Bee, WiMax, and cellular) categories [131]. Two data communication schemes are in use: centralized and distributed. In the centralized scheme, data from MG components are sent to a central control for processing and command transmission [132]. The distributed control involves data exchange among MG components and local processing to offer flexibility and robustness against failures. It demands complex algorithms and longer processing times, resulting in less data congestion and collisions. While communication in centralized control is hard to implement, it has scalability challenges and is susceptible to communication failures [133]. The communication layer is categorized into three levels (see Figure 2.26).

The first level involves connecting sensors to DG units and local control for data collection via serial connections. The second level involves communication between LCs in DGs and MGCC. At this level, sensor data are transmitted to MGCC, and control signals are propagated back to LC. Data transfer is formatted into sending packets, and a bandwidth of 1–100 kbps [134]. The third level manages communication between interconnected MGs, with higher data rates [135].

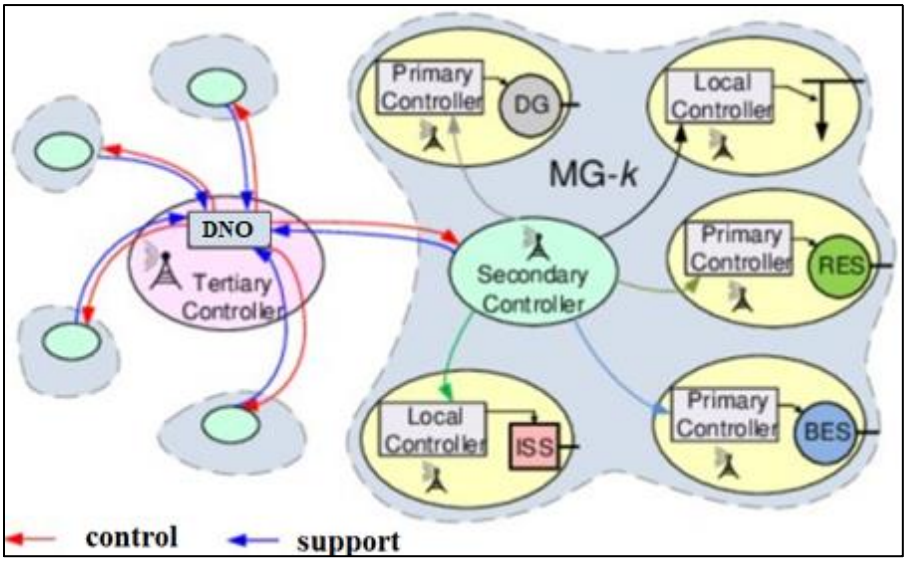

Figure 2.26: Typical Description of The Communication Layer.

The communication layer in MG control topologies help to ensure efficient and coordinated operation among MGs resources. Various communication topologies are employed to facilitate data exchange and control commands within a MG. There are several common communication layer topologies used in MG control systems:

a. All-to-All Topology: In this configuration, every node can communicate with every other node in MG system. It offers high connectivity, allowing information exchange among all components. This topology demands less communication bandwidth [136].

b. Loop Topology: In a loop topology, nodes are connected in a circular hub. This arrangement facilitates continuous data flow within the loop, enhancing fault tolerance. Loop topology is effective for MGs components scattered in wide geographical areas [137].

c. Mesh Topology: Mesh topology involves multiple interconnected nodes; each node is directly linked to several nodes. It is robust structure ensures reliable communication routes. Mesh network is resilient against individual node failures since it offers multiple routes for data transmission, prevents collision and congestion, hence enhancing reliability [138].

d. Daisy Chain Topology: In a daisy chain topology, each node communicates with the preceding and succeeding nodes, simplifies wiring. However, it is vulnerable to communication disruptions if one node in the chain fails and suffers congestion [139].

e. Star Topology: Star topology contains hub point to which all nodes are connected. All communication passes through the central hub, simplifying management. A failure in the central hub can disrupt communication across the entire MG communication layer [140].

f. Hybrid Topology: Many MGs employ a combination of the above topologies, based on the specific requirements of different components. It leverages the strengths of multiple configurations to enhance communication efficiency and reliability [141].

The communication topology determination depends on MG's size, geographical layout, communication infrastructure availability, and the level of complexity, redundancy, and fault tolerance required for reliable operation.

2.12.1 Graph Theory

There are several independent units in MGs need to communicate to achieve operation consensus. The communication relies on a graph structure proposed based on the system specifications, limitations, and data centers. The term 'simple graph' denotes a graph that is undirected, unweighted, and lacks multiple edges or loops [142].

A connected graph must establish a direct path connecting a minimum of two nodes, which in MGs case are generators and loads. The communication structure of this simple graph with vertices is represented by an n × m matrix known as the adjacency matrix (A) as shown in equation (2.5). The off-diagonal elements within the adjacency matrix ascertain whether there exists (node i to j) direct path. When dealing with undirected graphs, the adjacency matrix is symmetric. Each node's number within the graph is indicated by another matrix termed the degree matrix [143]. Within the degree matrix, the diagonal entries where $i=j$ signify the count of edges linked to node i, with all remaining matrix entries assigned zero values. The Laplacian matrix is derived through the collaborative contribution of the adjacency matrix and the degree matrix [144].

This resultant Laplacian matrix provides a representation of the communication topology and connectivity existing among all nodes in the graph, as illustrated in Figure 2.27. The value within the Laplacian matrix is computed to optimize the communication topology among MG nodes. This optimization is essential to ensure that all nodes within the graph converge to the best solution parameter.

$$A = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 \\ a_{21} & a_{22} & a_{23} & 0 \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & 0 & a_{43} & a_{44} \end{bmatrix} \quad (2.5)$$

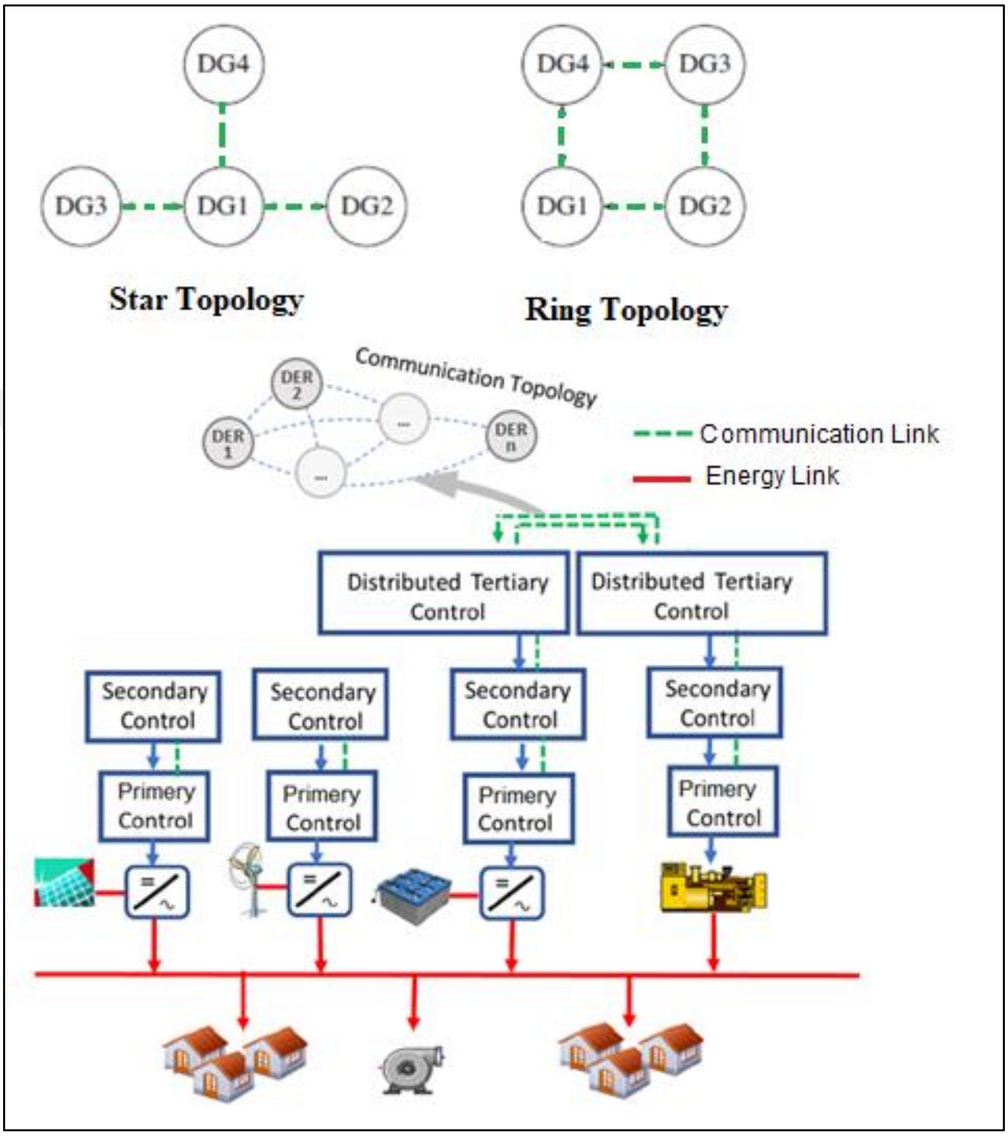

Figure 2.27: Different Graph Theory Communication Topologies.

3. MODELLING OF MICROGRID CONTROL

To ensure the accurate simulation of practical scenarios and the effective application of CFGSA-DO, it is imperative to establish a precise MG definition and model. This chapter explores the used PF simulation technique, MATLAB/Simulink, and addresses the challenges encountered in modelling DGs.

The subsequent sections evaluate the model's faithfulness to the real MG configuration, elucidating the modelling procedures applied in this thesis. The simulation software utilized is described, offering insights into MG model. Furthermore, this chapter explicates the challenges of the proposed control, shedding light on its fundamental mechanisms.

3.1 POWER SHARING OPTIMIZATION

Many simulators available in the market offer diverse modelling and analytical capabilities of energy, involving areas such as load flow studies, evaluations of transient stability, fault analyses, and power distribution assessments. Despite the advantages and limitations of each simulator concerning its functionalities and accessible electrical control blocks, modelling distributed generators encounters a shared challenge. This challenge stems from the weaker integration and network penetration of distributed generators when contrasted with conventional synchronous generators. Moreover, the attributes of RESs and the accompanying control technologies exert a significant influence on the nature, internal mechanisms, and dynamics of distributed generators. A notable concern arises from the assumption made by these simulators, positing a constant overall frequency throughout the electrical system [145], [146].

This assumption presents a considerable hurdle in analysing the dynamics of power flow within MGs. Given this presumption, MGs, due to their scale and inherent traits, experience substantial frequency fluctuations in response to varying heavy loads. To address this issue, researchers often incorporate additional P-f droop features into the frequency control systems of MG generators, imitating PCC fluctuations corresponding to changes in substantial loads. However, this focus revolves around voltage stabilization within MGs through a CF-GSA algorithm, diminishing the relevance of challenges in frequency control [147].

In our simulation modelling efforts, a constant frequency premise has been adopted to concentrate on voltage stability. Various types of DGs exist, each with internal functionalities. The behaviour of loads, distribution, and transmission infrastructure is also regulated by the typical droop system. Ensuring that new distributed generation replicates the attributes of standard synchronous generators is imperative for the practical and economic integration of MGs into existing power systems. Therefore, the effective approach for MG modelling and load flow calculations involves assuming that DGs behave to synchronous generators, without significant deviations from their actual behaviour. The simulation modelling undertaken in this thesis is constructed upon this specific premise [148].

3.2 MICROGRID MODELING

Of energy research, the MATLAB/Simulink program stands out as a preferred choice among scholars due to its extensive array of controls, simulation capabilities, and analytical tools. Renowned for its user-friendly interface and a substantial library of electrical components, this software offers researchers the flexibility to customize tool operations according to their specific needs. In previous sections, the distributed generators have been represented using a 3-phase synchronous generator model.

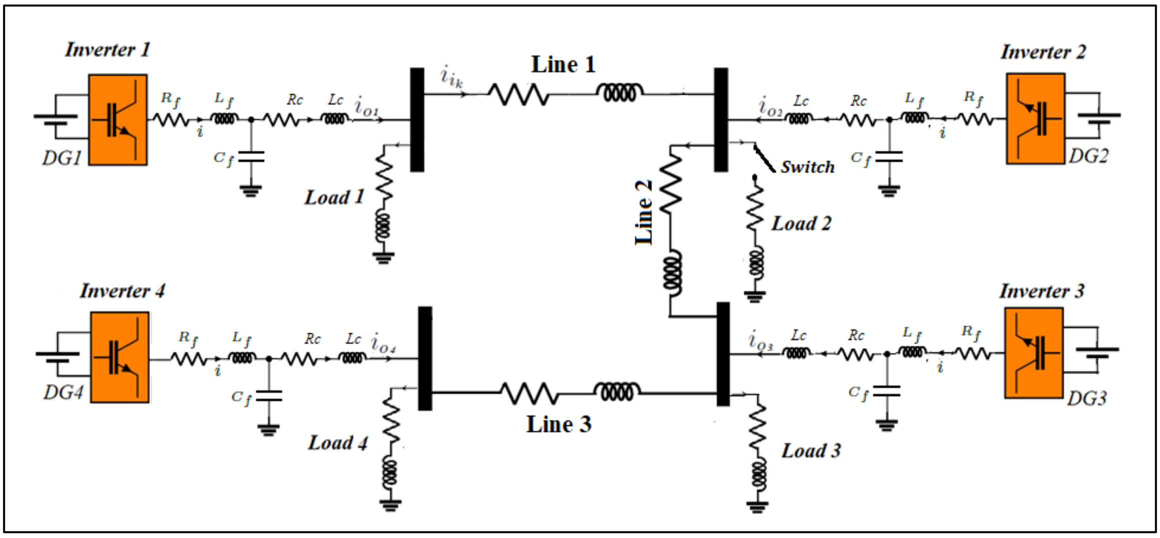

Figure 3.1: Four DGs Microgrid Block Diagram.

This model incorporates external feedback mechanisms determining the output frequency, desired phase angle, DGs voltage (V_j) (set at 311 volts). Q is influenced by voltage amplitude, while the output of P is governed by frequency and phase angles. The study focuses on controlling power and stabilizing V_j, thus maintaining a fixed frequency input at 50 Hz. Each DG is assigned the necessary phase angle for a predetermined P dispatch, facilitated by droop control system [149].

This experimental work implemented a radial MG configuration, comprising four DGs with distribution buses. Illustrated in Figure 3.1, this independent MG system features control area buses, each with a load capacity of 200 VAr and 5.8 MW. These DGs are designed as DC RESs equipped with VSIs, emulating low inertia characteristics. Thus, they are susceptible to fluctuations in V-f due to interruptions in the power generated and dynamic changes in resistive and inductive loads within the switched load on bus 2. Maintaining stable V-f levels is crucial to bridge the generation gap and meet the demand. To achieve this, integrating an optimized droop control mechanism is under consideration.

Operating in PQ mode, VSIs can establish V-f references, when connected to a medium-voltage grid, ensuring autonomous operation for MGs without the need for communication or mode control requirements [150]. The capability to operate and synchronize with other voltage sources, including fellow VSIs, characterizes VSIs. This parallel functionality facilitates the efficient distribution of the load demand among diverse DGs based on their ratings, achievable through the application of PC mechanisms. Illustrated in Figure 3.2, this control process utilizes reference V-f signals to regulate the VSIs.

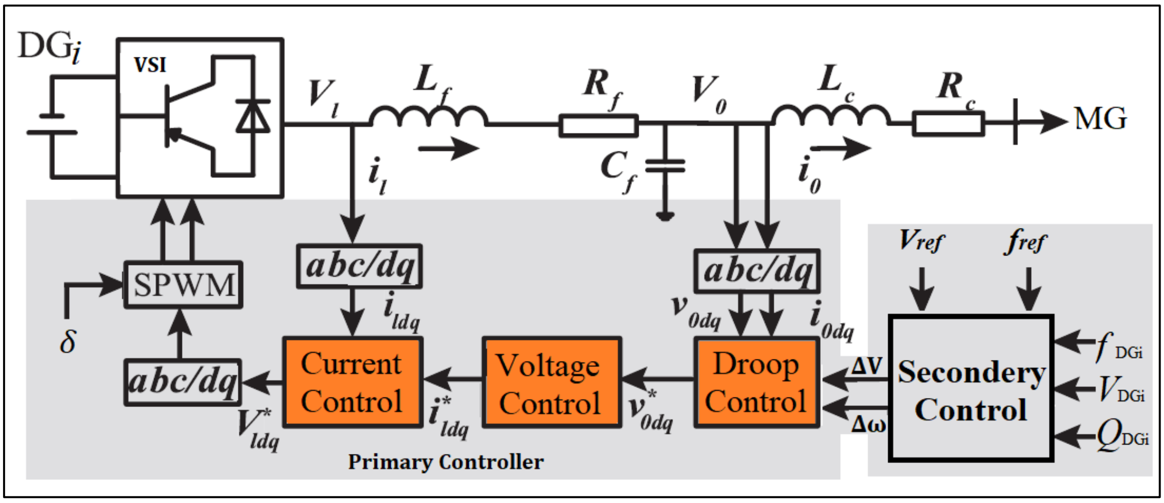

Figure 3.2: VSI Control Loops for DGs.

The Sinusoidal Pulse Width Modulation (SPWM) switching technique is employed for VSI regulation, utilizing signals emanating from PC. To facilitate the connection of multiple inverters, the load and line currents are represented in the shared d-q frame. Addressing concerns related to PS, Model Predictive Control adjusted control capable of real-time optimization are deployed.

This approach hinges on several fundamental prerequisites, which will be elaborated upon in the ensuing discussion, to generate controlled variables within the control system. The adept management of dynamic V-f fluctuations relies upon these specific characteristics. The aim of CFGSA-DO is to implement predictive criteria across a prediction horizon while adhering to response constraints.

The model calculates the next control actions ensuring closed loop stability, minimizing response uncertainty based on bus ratings. Efficient control is essential for anticipating the future trajectory, a crucial aspect of this strategy. The optimization in this thesis focuses on PC loops, involving droop, voltage, and current regulation. In PC, the droop loop, a pivotal component, modulates the V-f of the DG inverter in response to load variations. Droop control technique induces a frequency decrease with an increase in load and vice versa. The voltage control loop maintains the $V_j$within predetermined limits, protection connected equipment from potential damage due to overvoltage or undervoltage.

3.3 DROOP CONTROL MODELING

During transient disturbances, PC droop mechanism, is influenced by classical synchronous generator governor principles. This autonomous regulation governs the power output of the connected VSIs, ensuring precise allocation among various distributed power sources within MG structure, as illustrated in Figure 3.3.

MG configuration involves network infrastructure, DGs, and load models. In this study, the four DGs model outlined in the source material is employed, integrating crucial elements such as droop control, current and voltage control models, LC filters, and coupling inductance. Unlike models in previous studies that neglected inverter gains, this study incorporates them, proving indispensable in enhancing the model's precision and facilitating a more thorough examination of stability parameters within the system [151].

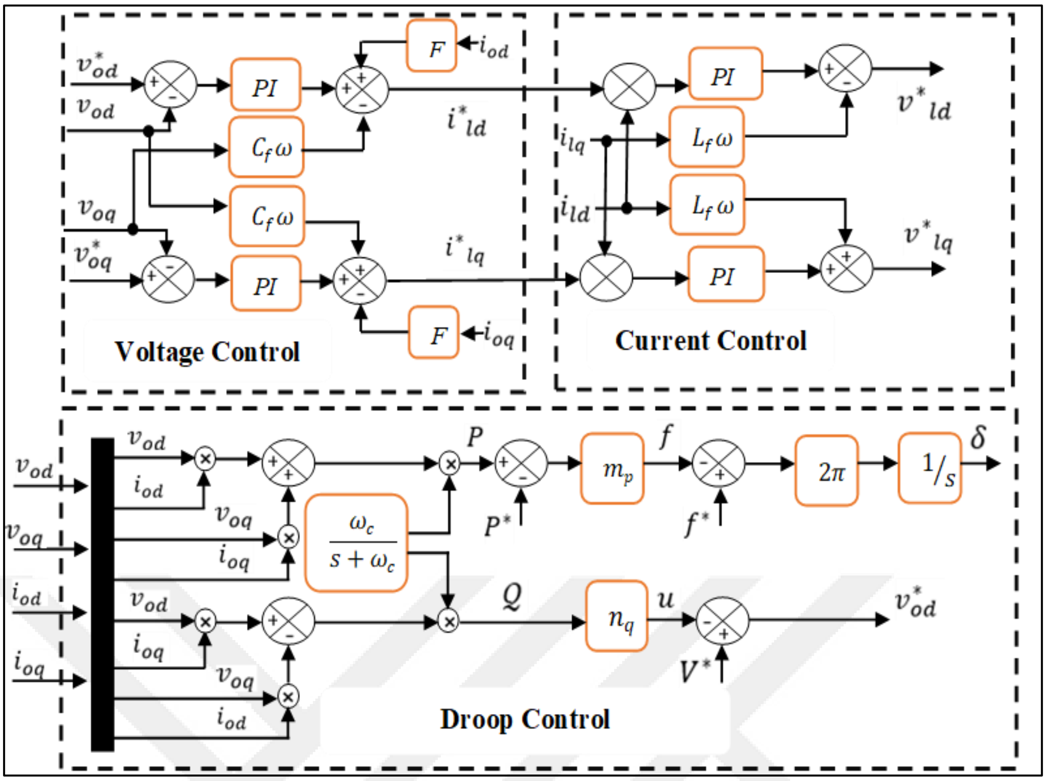

Figure 3.3: Modelling of Microgrid Primary Control.

3.3.1 Droop Model

The core idea underpinning PS involves preserving generation load demand balance through the modulation of V-f amplitudes using droop characteristics. This section emphasizes the complex mathematics and control logic involved in PS within parallel VSI systems. Understanding these principles is fundamental to achieving stable and efficient MG operation. Within parallel VSI, the frequency (ω) and voltage (v^*) parameters are dictated by droop coefficients, m_P and n_q as defined in the following:

$$\omega = \omega_n - m_P(P - P_n) \tag{3.1}$$

$$v^*_{od} = V_n - n_q(Q - Q_n) \tag{3.2}$$

$$dv^*_{oq} = 0 \tag{3.3}$$

The nominal frequency, Q, P, and voltage are denoted as ω_n, Q_n, P_n, and V_n, respectively. Q_n is considered zero. P and Q power computations are based on the measured current and voltage, represented in the d-q frame as i_{od}, i_{oq}, v_{od}, and v_{oq}. To guarantee enhanced power delivery quality, the average P and Q calculated utilizing a low-pass LCL filter with ω_c cut-off frequency of:

$$P = \frac{\omega_c}{s + \omega_c}(v_{od}i_{od} + v_{oq}i_{oq}) \tag{3.4}$$

$$Q = \frac{\omega_c}{s + \omega_c}(v_{od}i_{oq} - v_{oq}i_{od}) \tag{3.5}$$

The linearization at the equilibrium leads to the derivation of droop control model:

$$d\omega = -m_P dP \tag{3.6}$$

$$dv_{od}^* = -n_P dQ \tag{3.7}$$

$$dv_{oq}^* = 0 \tag{3.8}$$

$$d\dot{P} = -\omega_C dP + \omega_C(I_{od}dv_{od} + I_{oq}dv_{oq} + v_{od}di_{oq} + v_{oq}di_{oq}) \tag{3.9}$$

$$d\dot{Q} = -\omega_C dQ + \omega_C(I_{oq}dv_{od} - I_{od}dv_{oq} - v_{oq}di_{od} + v_{od}di_{oq}) \tag{3.10}$$

The angular difference denoted as a_d enables reference to common frame references. The system frequency, ω_1, sets the frequency of the first VSI (of DG_1). Hence, ad is modelled as following:

$$d\dot{a}_d = -mPdP - d\omega_1 \tag{3.11}$$

3.3.2 Voltage Loop

In the voltage loop, a reference d-q coordinate current vector, designated as i_{ld}^* and di_{lq}^*, is generated. Figure 3.3 illustrates the block diagram of the voltage loop, incorporating two traditional proportional-integral (PI) controls with proportional-integral coefficients, K_{pv}, and K_{iv}, and a feed-forward term defined by gain F. The voltage control loop is modelled as follows:

$$d\dot{\emptyset}_d = dv_{od}^* - dv_{od} \tag{3.12}$$

$$d\dot{\emptyset}_q = dv_{oq}^* - dv_{oq} \tag{3.13}$$

$$di_{ld}^* = k_{iv}d\emptyset_d + k_{pv}(dv_{od}^* - dv_{od}) - \omega_n C_f dv_{oq} + Fdi_{od} \tag{3.14}$$

$$di_{lq}^{*} = k_{iv}d\emptyset_q + k_{pv}\left(dv_{oq}^{*} - dv_{oq}\right) + \omega_n C_f dv_{od} + Fdi_{oq} \quad (3.15)$$

Where (v_{oq}) is loads voltage, and v_{oq}^{*} is reference voltage from power calculation control block.

3.3.3 Current Loop

The current loop operates by generating the output reference SPWM voltage, represented as v_{id}^{*} and v_{iq}^{*}. This process involves comparing the current sample values, i_{lq}^{*} (representing the d-component of reference current and i_{lq} representing the q-component of load current with the filtered current reference, utilizing the filtered current reference. The comparison involves the application of a Proportional-Integral (PI) control, a common control technique ensures precise adjustment based on the deviation between the desired and actual values. The Proportional-Integral control functions by considering both the current error's immediate value (proportional term) and the accumulated historical errors over time (integral term). By incorporating these factors, the control can minimize imbalances between the desired and actual current values. This process is crucial in maintaining the stability and accuracy of the current flow within the system, ensuring that the generated power aligns with the intended requirements of MG or electrical grid. The model for the current loop is articulated as follows:

$$d\dot{r}_d = di_{ld}^{*} - di_{ld} \quad (3.16)$$

$$d\dot{r}_q = di_{lq}^{*} - di_{lq} \quad (3.17)$$

$$dv_{id}^{*} = k_{ic}dr_d + k_{pc}(di_{ld}^{*} - di_{ld}) - \omega_n L_f di_{lq} \quad (3.18)$$

$$dv_{iq}^{*} = k_{ic}dr_q + k_{pc}\left(di_{lq}^{*} - di_{lq}\right) + \omega_n L_f di_{ld} \quad (3.19)$$

3.3.4 Impedance Filter and Coupling Inductance

The elimination of harmonics of the switching frequency in the connection of VSI to MG is facilitated by the impedance LC filter and the DG line inductance (L_c). In certain references, an assumption is made that v_i^{*} is similar to v_i. However, inverter gain is vital to consider since SPWM is substantial to form the required DG outputs. Neglecting this factor causes imprecise outcomes. The interrelation among these variables is shown as:

$$v_{idq} = v_{idq}^{*} \frac{K_{\mathrm{SPWM}}}{0.5\, T_S S + 1} \tag{3.20}$$

The PWM gain, represented as K_{SPWM}, corresponds to DC source voltage and carrier amplitude. This correlation becomes crucial when the VSI sampling time, denoted as T_S, reaches its minimum value.

$$v_{idq} = v_{idq}^{*} K_{\mathrm{SPWM}} \tag{3.21}$$

The impedance modelling for the DG-MG coupling is as follows:

$$d\dot{i}_{ld} = -\frac{R_f}{L_f} di_{ld} + \omega_O di_{lq} - \frac{1}{L_f} dv_{od} + \frac{K_{SPWM}}{L_f} dv_{id} + I_{lq} d\omega \tag{3.22}$$

$$d\dot{i}_{lq} = -\omega_O di_{id} - \frac{R_f}{L_f} di_{lq} - \frac{1}{L_f} dv_{oq} + \frac{K_{SPWM}}{L_f} dv_{iq} - I_{ld} d\omega \tag{3.23}$$

$$d\dot{i}_{od} = \frac{1}{L_c} dv_{od} - \frac{R_c}{L_c} di_{od} + \omega_O di_{oq} - \frac{1}{L_c} du_{bd} + I_{oq} d\omega \tag{3.24}$$

$$d\dot{i}_{oq} = \frac{1}{L_c} dv_{oq} - \omega_O di_{od} - \frac{R_c}{L_c} di_{oq} - \frac{1}{L_c} du_{bq} - I_{od} d\omega \tag{3.25}$$

$$d\dot{u}_{od} = \frac{1}{C_f} di_{ld} + \omega_O dv_{oq} - \frac{1}{C_f} di_{od} + v_{oq} d\omega \tag{3.26}$$

$$d\dot{u}_{oq} = \frac{1}{C_f} di_{lq} - \omega_O dv_{od} - \frac{1}{C_f} di_{oq} - v_{od} d\omega \tag{3.27}$$

3.3.5 VSI Model

Incorporating the inverter in MGs necessitates the conversion of output variables i_{odq} and the input v_{bdq}variable in shared reference. This transformation yields output and input variables in a common d-q coordinate system, as shown by the following equations:

$$[d\dot{i}_{oDQ}] = \begin{bmatrix} \cos(ad_o) & -\sin(ad_o) \\ \sin(ad_o) & \cos(ad_o) \end{bmatrix} [d\dot{i}_{odq}] + \begin{bmatrix} -I_{od}\, sin(ad_o) & -I_{oq}\, cos(ad_o) \\ I_{od}\, cos(ad_o) & -I_{oq}\, sin(ad_o) \end{bmatrix} [da_d] \tag{3.28}$$

$$[dv_{bDQ}] = \begin{bmatrix} \cos(ad_o) & \sin(ad_o) \\ -\sin(ad_o) & \cos(ad_o) \end{bmatrix} [dv_{bdq}] + \begin{bmatrix} -v_{bd}\, sin(ad_o) & v_{bq}\, cos(ad_o) \\ -v_{bd}\, cos(ad_o) & -v_{bq}\, sin(ad_o) \end{bmatrix} [da_d] \tag{3.29}$$

This research introduces and examines a sophisticated PC system designed for DGs. Its objective is to optimize the distribution of power among DGs within an MG by employing

CF-GSA. Designed to enhance PS during routine operation and in the aftermath of disturbances, this control system operates within PC layer, addressing critical functions such as PS, power quality maintenance, and preserving V-f stability. Within this layer, precise control is exerted over current and voltage loops through Proportional-Integral (PI) control, with meticulous adjustments made in response to the dynamic conditions of MGs. The optimization process entails the collection and preprocessing of diverse datasets, involving information about individual DGs, load requirements, as well as V-f levels at DGs buses.

This model relies on fundamental principles, including MG regulated model, MG control response history, and the control cost functions. These principles form the basis for optimizing PC ensuring its effectiveness in various operational scenarios. The CFGSA-DO adjusts two primary gains: Proportional coefficient K_{pc} in current loop and Integral coefficient K_{iv} in voltage loop. Constants K_{ic} and K_{pv} are set to fixed values, 6.35 and 0.0029 respectively. Within the PI controller of both current and voltage control, the transfer function (GPI) is defined as follows:

$$G_{PI} = K_p + \frac{K_i}{S} \tag{3.30}$$

In droop loop, power imbalances in autonomous mode, leading to fluctuations in V-f, are mitigated by the corresponding droop characteristics [152]. This control principle obviates the urgent need for communication between DGs and the central control (in SC layer), as VSIs can respond to system disturbances based on available terminal information. Thus, MGs employ the Single-Master Operation (SMO) method when a single VSI suffices to establish V-f references. However, this work adopts the Multi-Master Operation (MMO) approach, wherein all VSIs are managed by droop regulation functions [153]. In case of unexpected disturbances, VSIs governed by droop functions rectify power imbalances and redistribute power variations according to their specific droop characteristics. Droop coefficients, denoted as m_P and n_q, play a crucial role in balancing power and ensuring V-f stability. Equation (3.31) delineates power imbalance *dP* as represented by:

$$dP_l = \sum_{i=1}^{n} dP_i \tag{3.31}$$

$\boldsymbol{dP_l}$ is the varying load power and $\boldsymbol{dP_i}$ is power generated by DGs.

$$\begin{vmatrix} 1 & m_p1 & 0 & 0 & 0 \\ 1 & 0 & m_p2 & 0 & 0 \\ 1 & 0 & 0 & m_p3 & 0 \\ 1 & 0 & 0 & 0 & m_p4 \\ 0 & 1 & 1 & 1 & 1 \end{vmatrix} \times \begin{vmatrix} \omega' \\ \boldsymbol{dP_1} \\ \boldsymbol{dP_2} \\ \boldsymbol{dP_3} \\ \boldsymbol{dP_4} \end{vmatrix} = \begin{vmatrix} \omega_{MG} \\ \omega_{MG} \\ \omega_{MG} \\ \omega_{MG} \\ \boldsymbol{dP_l} \end{vmatrix} \tag{3.32}$$

$\omega'$is the frequency after disturbance and $\omega_{MG}$is frequency before disturbance.

As explained above, droop coefficients play a crucial role in ensuring optimal power distribution. Updating these coefficients using an intelligent optimizer improves the system's responsiveness and adaptability to different transient disturbances. The implementation of droop control leads to fluctuations in both V-f. The key benefit of droop control lies in its ability to facilitate PS without requiring a communication link, providing the system with flexibility and autonomy [154]. Figure 3.4 illustrates droop curves, as defined in equations (3.2) and (3.3), showcasing the deviations following each disturbance event.

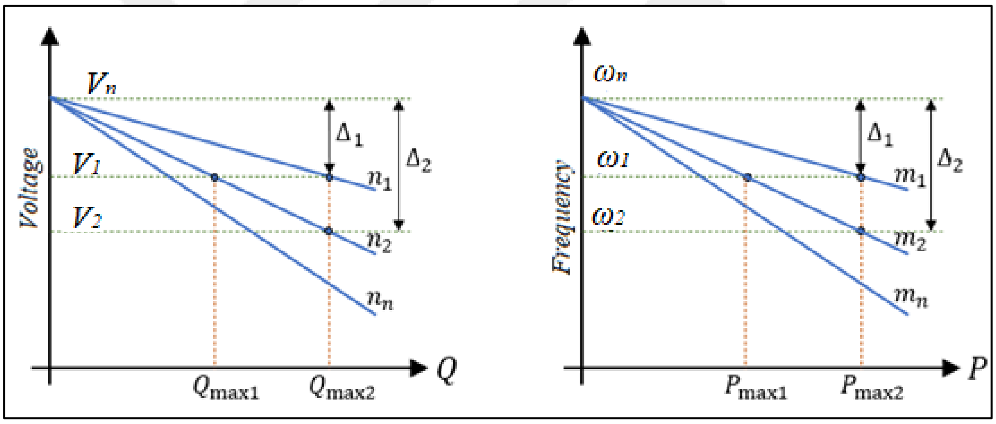

Figure 3.4: Droop V-f Deviations

3.4 CENTRIPETAL FORCE–GRAVITY SEARCH ALGORITHM

The Gravity Search Algorithm (GSA) is grounded in Newton's second law and the principle of gravity, stating that all natural entities exert mutual attraction. This gravitational pull is linked to the product of the objects' masses and inversely associated with the distance separating them. This fundamental concept suggests an inherent attraction among particles within the exploration space, guiding them towards areas with greater mass. The motion of these objects within space adheres to Newton's second law, which links an object's acceleration to the force acting upon it and its mass [155]. Through iterative processes, the entire population gravitates towards individuals of enhanced quality. Many applications are optimized using the concept of GSA as shown in Figure 3.5. On the other hand, centripetal force represents the resultant force experienced by an object in circular motion, pointing towards the center of the circle. In celestial motions, such as stars orbiting other celestial bodies, gravity serves as the Centripetal Force (CF). This CF principle is integrated into the GSA, resulting in CF-GSA optimization. In this framework, CF is proportional to an object's linear velocity and mass, while inversely related to the spacing between objects. As mass increases, orbiting objects (such as planets) draw closer to the center (such as the sun), facilitating the discovery of the global optimum.

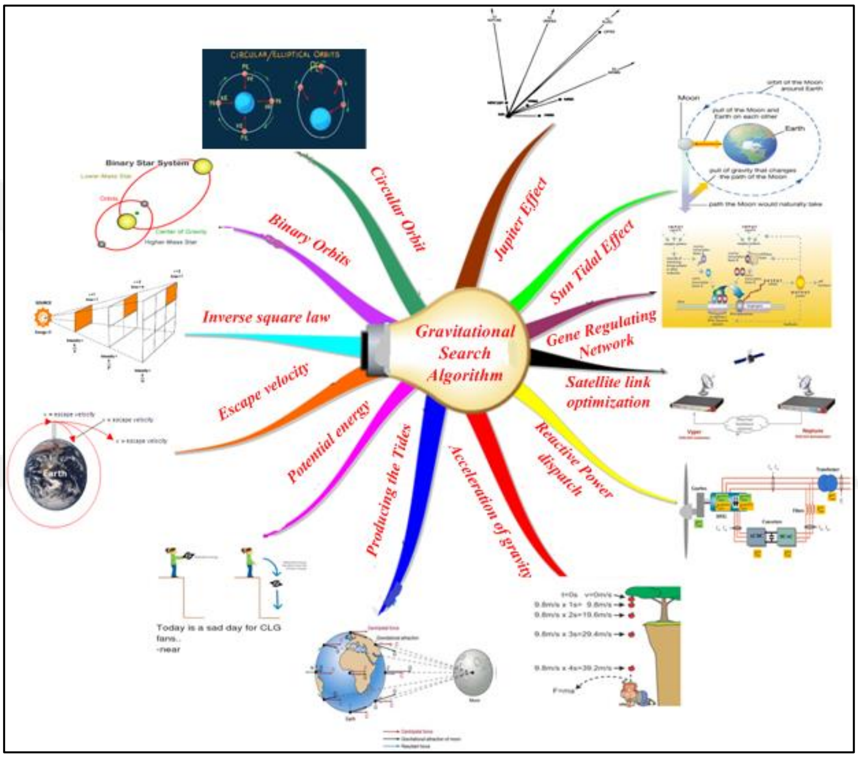

Figure 3.5: Gravity Search Algorithm Principles and Application.

Thus, higher linear velocity and decreased distance produce similar effects. The mathematical representation of CF is provided in formula (3.33).

$$F = \frac{M\ U^2}{R} \tag{3.33}$$

F represents the centripetal force between two or more objects, while U indicates the linear velocity of the object, and R signifies the distance between them. To simplify computational processes, the mathematical expression for U is streamlined by eliminating the square root, resulting in the following expression:

$$U = \frac{F \times R}{M} \tag{3.34}$$

During gravitational exploration, the object (planet) possessing higher mass moves more towards the central (sun) optimum. Thus, the effectiveness of the exploration agent is dictated by its mass, denoted as M. Moreover, the distance of the exploration agent from the optimum is symbolized by the parameter R. Over successive stages, the formula for velocity modification is redefined, as depicted in equation (3.35):

$$U(t+1) = \frac{\left(fit - fit_g\right) \times Dis\left(x, x_g\right)}{fit} \tag{3.35}$$

The term fit represents the current search agent fitness, fit_g denotes the fitness at a specific iteration, and $Dis(x, x_g)$ signifies the distance between the global optimum and search agent. Therefore, the position formula outlined in equation (3.36) is deduced based on U.

$$X(t+1) = U(t) + U(t+1) \tag{3.36}$$

In CF-GSA, a focused local search approach is employed instead of random exploration within a solution neighborhood, aiming to identify a single optimal solution. First, a population of potential solutions is initialized, optimized, and refined depending on the targeted problem. Thus, conducting intensive search to identify the highest fitness solution, indicating proximity to the global optimum. Illustrated in Figure 3.6, the sequential steps in the CF-GSA procedure for determining the required droop coefficients are shown as follows:

Recognition of search space: The boundaries of the search space are defined, as detailed in Table (3.1).

Population initialization: The population of candidate solutions, denoted as X_i, is initialized. Here, X_i^* represents the best solution closest to the global optimum.

Fitness calculation: The fitness value for each search agent is computed.

Deviation determination: Deviations for agents within the generated population are assessed. Adjustments to parameters (m_p, n_q, K_{pv}, and K_{ic}) are made to minimize these deviations.

Position and speed update: The velocity and position of agent are updated using equations (3.35) and (3.36).

Boundary check: Verification is performed to ensure no search agent surpasses the boundaries of the search space.

Fitness evaluation: The fitness of the search agents is calculated, and if enhanced fitness is identified, the global optimum X_i^* is updated.

Table 3.1: The Parameters Search Space Boundaries.

Classical Methods	Value domain
m_P	2 × 10^{-6} – 2 × 10^{-5}
n_q	9× 10^{-4} – 2 × 10^{-2}
K_{iv}	5 – 80
K_{pc}	2 × 10^{-4} – 2 × 10^{-2}

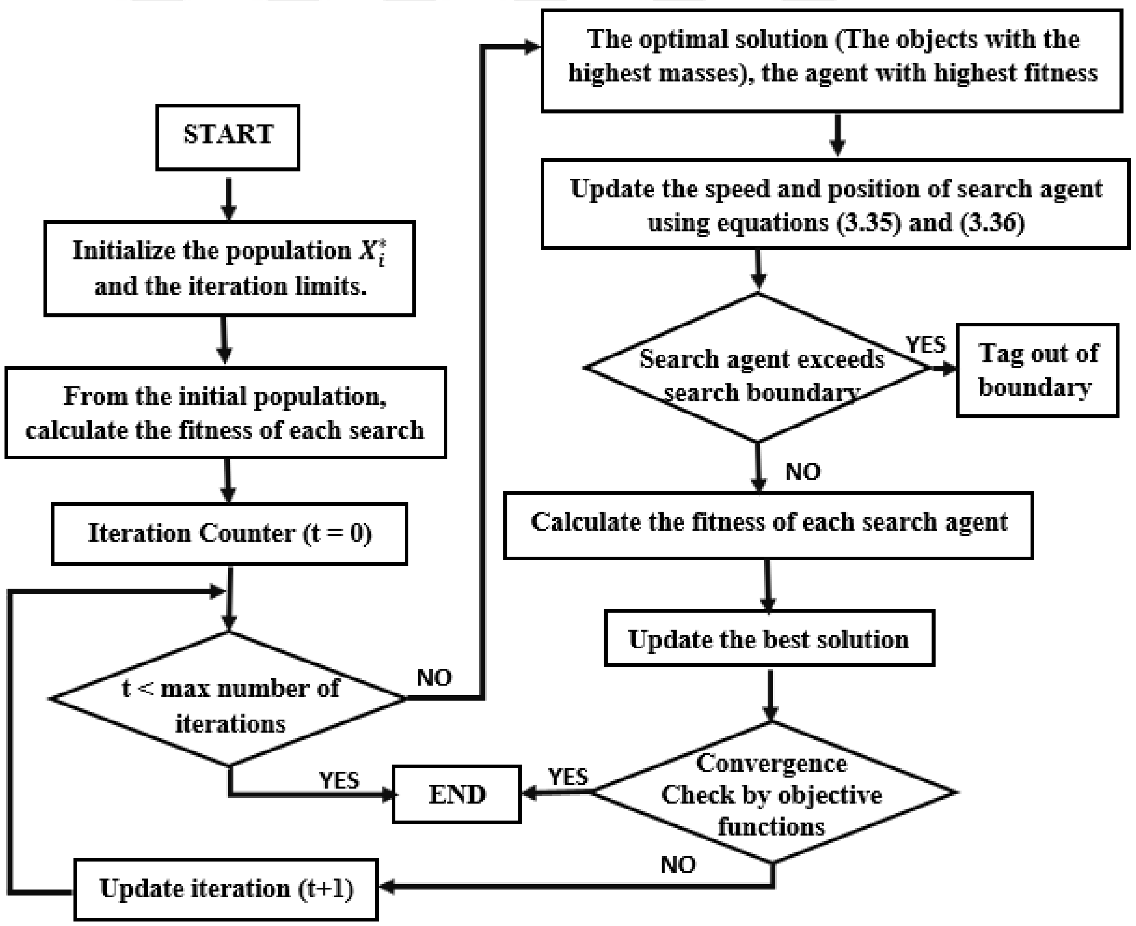

Figure 3.6: Flowchart of CF-GSA Optimization Processing.

3.5 OPTIMIZATION MULTI-OBJECTIVE FUNCTION

The examined case study involves three objectives that require attention. To facilitate MG ability to transition across different operational scenarios, it is essential to formulate an objective function, denoted as M. This objective function involves stability considerations and the smooth switching between these modes. Evaluation metrics for stability include adjustment time, V_j fluctuations, and PS [156], emphasizing the need for stability assessment. To avoid bias towards minimizing power share errors, the raw deviations are standardized to the order of 10^{-3}. This work formulates three separate objective functions: one assessing power quality, PS, and regulation time. Each of these objectives plays a vital role in ensuring MG efficient operation. M represents MG operational status of autonomous scenarios, N is DGs number.

3.5.1 Power Quality Objective

The assessment of power quality revolves around V_j, a critical indicator. Although droop control provide efficient power regulation, it can induce V_j deviations concerning the rated value [157]. These fluctuations, whether exceeding or falling below the expected values, have the potential to harm components, thereby compromising power quality. To quantify this phenomenon, the deviation of V_j from its rated value is measured and then normalized.

This normalization process is crucial as it establishes the loss rate. The objective remains the minimization of this loss rate, with a specific focus on the disparity between V_j and nominal voltage V^*. This relationship is represented as an equation, signifying the core focus of the study on ensuring optimal power quality within MG system.

$$f_1 = \sum_{i=1}^{M} \left\{ \frac{1}{N} \sum_{j}^{N} \left| 1 - \frac{V_j}{V^*} \right| \right\} \tag{3.37}$$

3.5.2 Power Sharing Objective

Generated power is a crucial indicator of system response, with the objective of droop control being the efficient distribution of power among inverters [158]. Precise power allocation indicates robust response; however, imbalances in line and load impedances result in errors in PS. This thesis focuses on minimizing the deviations in both P and Q to evaluate power distribution. The emphasis is on timely responses, making this objective function important to the research.

$$f_2 = \sum_{i=1}^{M} \left\{ \frac{1}{N} \sum_{j}^{N} \int_{t_o}^{t} \left[\left(\frac{P_j - P_j^*}{P_j^*} \right)^2 + \left(\frac{Q_j - Q_j^*}{Q_j^*} \right)^2 \right] dt \right\} \tag{3.38}$$

P_j and Q_j are output powers, P_j^* and Q_j^* are the desired values for various scenarios, given by:

$$P_j^* = \frac{S_j}{S_{Total}} P_{Total} \tag{3.39}$$

$$Q_j^* = \frac{S_j}{S_{Total}} Q_{Total} \tag{3.40}$$

S_j is DG power capacity, S_{Total}, P_{Total}, and Q_{Total} are the total loads.

3.5.3 Regulation Time Objective

The duration (T_s) is defined according to the conventional control concept, indicating the minimum time required to control the instantaneous power to attain and sustain V-f levels within ±0.5% and ±0.005% of its median value, respectively [159]. Criterion (3.43) guarantees the min time of optimized control.

$$T_s\text{: min} \left\{ t_s \left| \frac{P_j - P_j^*}{P_j^*} \right| \leq 0.1\% \right\} \tag{3.41}$$

Therefore, the regulation time objective function is:

$$f_3 = \sum_{i=1}^{M} \frac{1}{N} \sum_{j=1}^{N} T_s \tag{3.42}$$

The multi-objective functions (3.38) – (3.44) must be solved to fulfil CFGSA-DO. The general objective function is $F(x)$.

$$\begin{cases} F(x) = \left(f_1(x), f_2(x), f_3(x)\right) \\ x_1 \leq x_i \leq x_n, i = 1,2, \dots, N \end{cases} \tag{3.43}$$

Also, this optimization relies on an intensification mechanism outlined in Table 3.1 to define the search space to perform these objectives. The intensification mechanism, guided by the designer's expertise, is employed to minimize search time by focusing research efforts on this promising research space instead of exploring a broad search space range.

3.6 PROPOSED CONTROL APPROACH

In Figure 3.7, the MG is monitored by CFGSA-DO, which adjusts the control coefficients, offering an adaptive solution capable of handling diverse operating conditions and disturbances. This optimization structure predicts control signals using an enhanced algorithm model. Its inputs comprise previous control moves, the current system state, and the desired referenced control actions. The tuning process, guided by the cost function and manipulated input and output constraints, executes these adjustments. The optimized droop's predicted output and the actual error contribute to formulating the optimal PS control [160]. The fine-tuned droop is to diminish the actual discrepancy, aiming for values nearing zero. Steering this fine-tuning process is the expense function, required by a weighted total of forthcoming discrepancy values and anticipated output squares. The dynamic behavior of the system is depicted through information collected across diverse operational situations during a designated period. Initial processing stages, including normalization and standardization, are utilized to attain consistent data scaling. Also, scrupulous handling of any absent or conflicting data is conducted to uphold the integrity of the dataset [161].

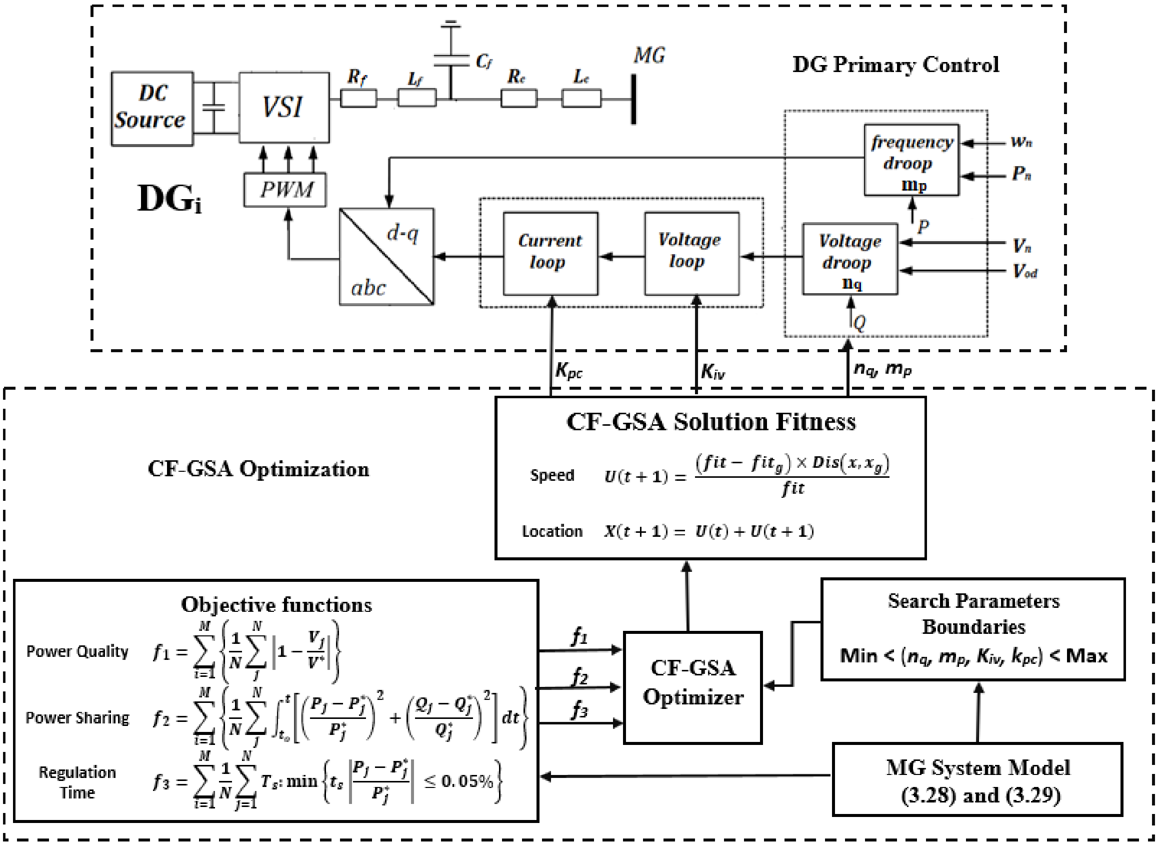

Figure 3.7: The Proposed Optimization in Primary Control Layer.

In preparation for CF-GSA model optimization, the dataset undergoes preprocessing to ensure consistent scaling and data quality. The refined dataset is then applied to the CF-GSA model optimization for MG parameters, predicting precise control actions based on the system's state. Model response evaluation utilizes a dataset segment. Throughout the optimization process, objective functions are proposed to ensure PS while keeping PCC V-f within acceptable levels.

4. PROPOSED WORK RESULTS AND DISSCUSIONS

In this chapter, simulation case studies have been conducted under CFGSA-DO utilizing various communication topologies with radial MG model using MATLAB/Simulink. The proposed control's effectiveness is assessed through simulations of the radial MG shown in Figure 3.1. The validation scenarios cover many conditions that are commonly encountered by MGs. These conditions include variation in inductive load, unexpected DG trips, and SC failures due communication topology weakness and communication delays. Detailed MG model specifications and ratings are listed in Table 4.1.

Table 4.1: The Radial Microgrid Specifications.

Component	Rating
System phase voltage peak amplitude (V)	$220\sqrt{2}$ = 311.13
DG DC Voltage (V)	700
AC PCC frequency (Hz)	50
Resistance of impedance filter Rf (Ohm)	0.1
Inductance of impedance filter Lf (mH)	3.5
Shunt capacitor impedance filter Cf (μF)	50
DGi coupling line resistance Rc (Ohm)	0.05
DGi coupling line inductance Lc (mH)	0.35
MG lines resistance (Ohm)	0.15
MG lines inductance (mH)	0.35
Loads P (kW)	5.8
Load inductive power (kVAr)	0.2

These scenarios have been proposed to pose a challenge to MG stability, aimed at assessing the resilience and the CFGSA-DO adaptability. The radial connection is poor configuration compared to other topologies. Therefore, the radial topology control fail to counter V-f variations, and energy transmission challenges and aggregated line impedance, hindering power distribution. Thus, this MG adds complexity to control.

There are 3 cases used to validate CFGSA-DO under the MG model detailed in the last section: In the first case, load variation, case 2 evaluates CFGSA-DO robustness under the sudden DG disconnection, and case 3 explores CFGSA-DO robustness under SC failure. SC layer plays a crucial role to preserve V-f stability. However, delayed communication disrupts SC, leading to $V_j - f$ instability [162]. As a result, the proposed optimization is design to address fault compensation. While the first and second cases have used all-to-all communication topology, the third scenario adopts a weak (daisy chain) topology to assess CFGSA-DO to ensure acceptable stability even in weak communication topology suffering delay.

4.1 INDUCTIVE LOAD POWER SHARING

Inductive load PS is a common challenge to the MG operation, influencing both stability and efficiency. DERs contribute to total MG power generation, PS is difficult if the loads on each DG bus are not balanced and contain excessive inductive loads is required. Inductive loads, such as electric motors and transformers, introduce more Q requirements to MG. In PS, it is crucial to distribute this Q among the DGs which disturb the P generation stability hence MG's frequency regulation. This complicated process involves optimizing droop control mechanism to ensure maintaining V_j stability within MG. Also, unequal distribution of Q can lead to voltage imbalances, causing voltage deviations beyond acceptable limits. Without a careful design, reactive power sharing (RPS) can introduce fluctuations in frequency, thus the optimized PS mechanism must damp these fluctuations within the desired frequency range. Challenges of inductive load variation include the effect on the MG impedance which may affect the proper power sharing. Hence, CFGSA-DO is required to address these challenges while secure efficient these challenges to enhance the accuracy of PS and ensure effective inductive load compensation. Efficient distribution of Q among DERs enhance V-f regulation hence the stability of MG. Figures 4.1, 4.2, 4.3, and 4.4, show a comparison between CFGSA-DO and PSO-optimized droop with model predictive control. First, the radial MG operate with inductive loads 1, 2, and 3, while load 2 is switched off. Between 5-10 seconds, load 2 is switched ON to evaluate MG response under inductive load variations.

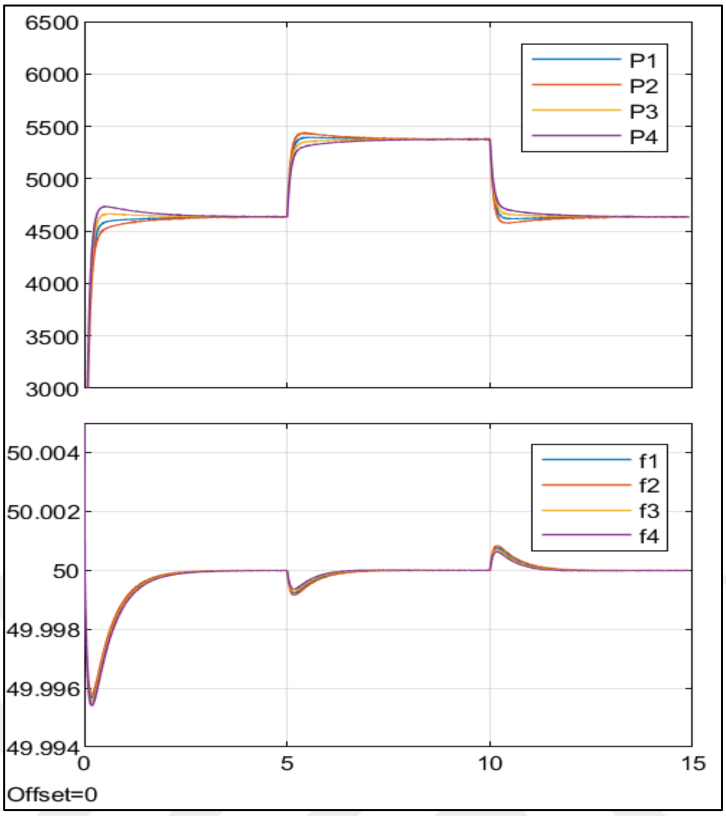

Figure 4.1: APS Response of PSO Optimization Control in [163].

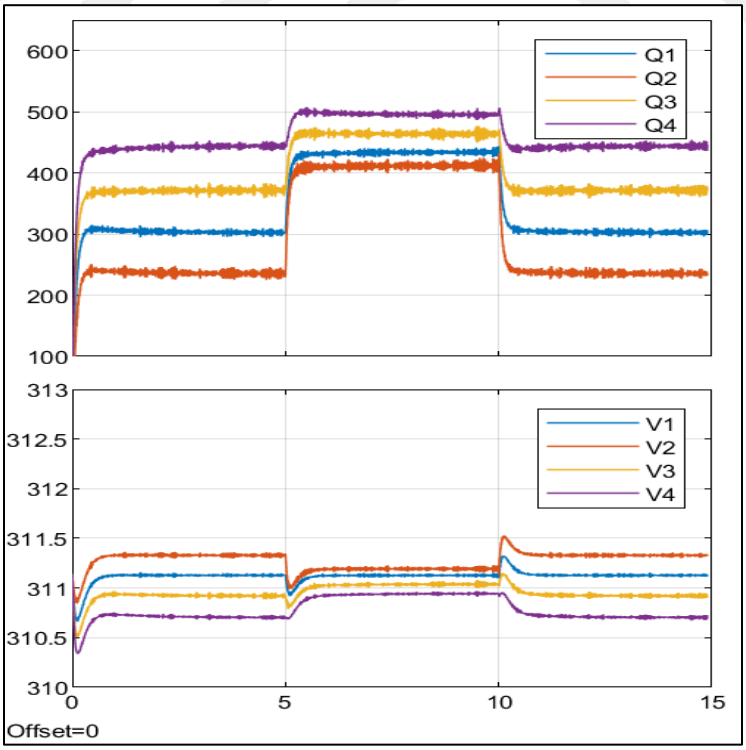

Figure 4.2: RPS Response of PSO Optimization Control in [163].

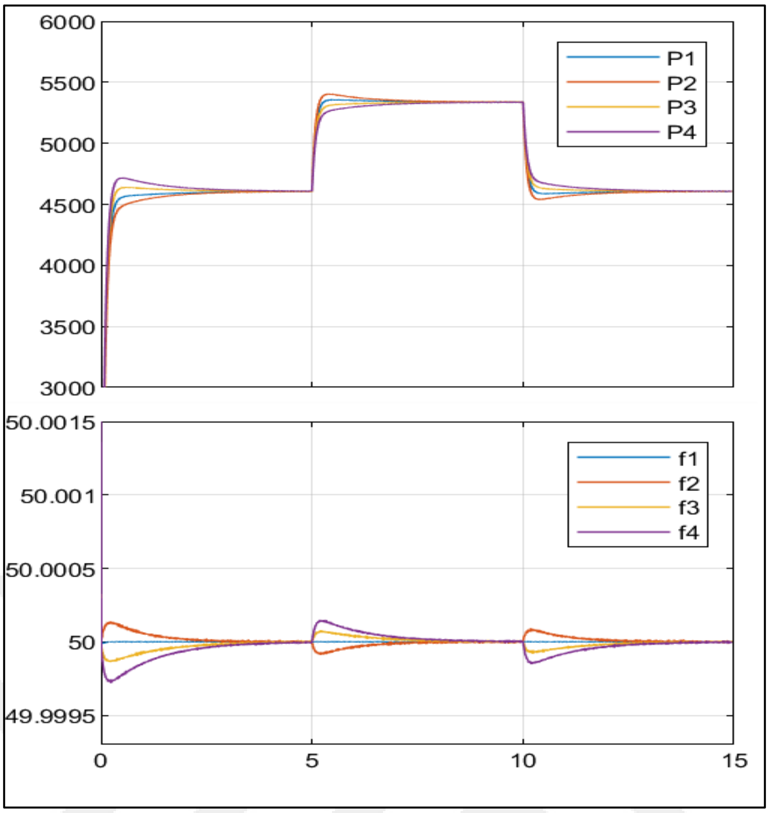

Figure 4.3: APS Response of CFGSA-DO Control.

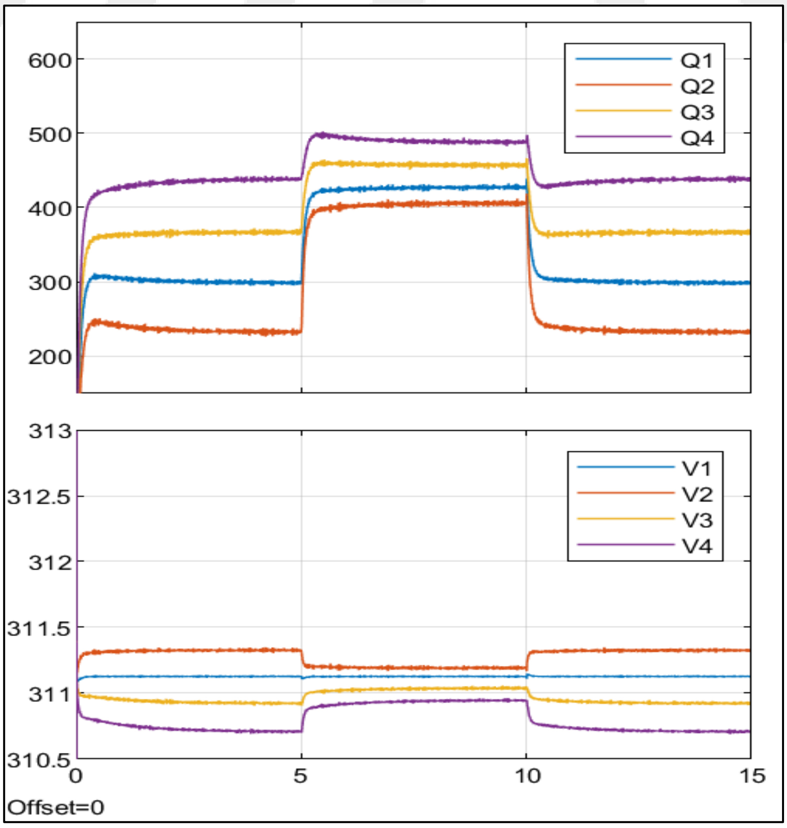

Figure 4.4: RPS Response of CFGSA-DO Control.

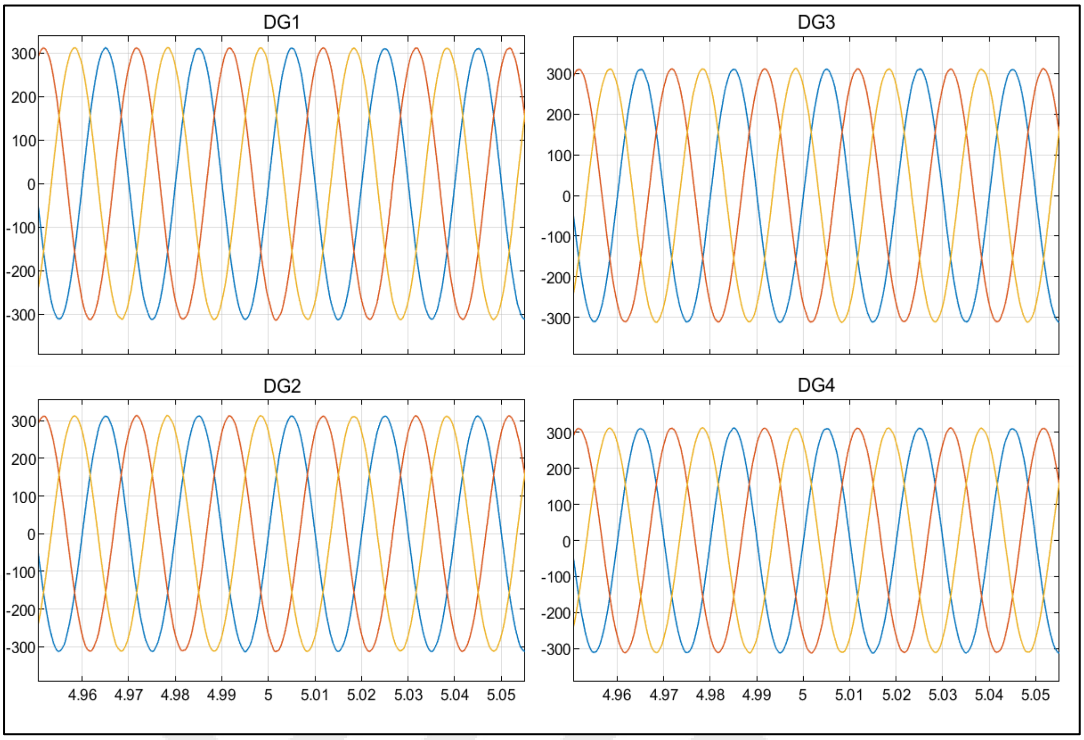

Figure 4.5: DG Voltages under CFGSA-DO Control.

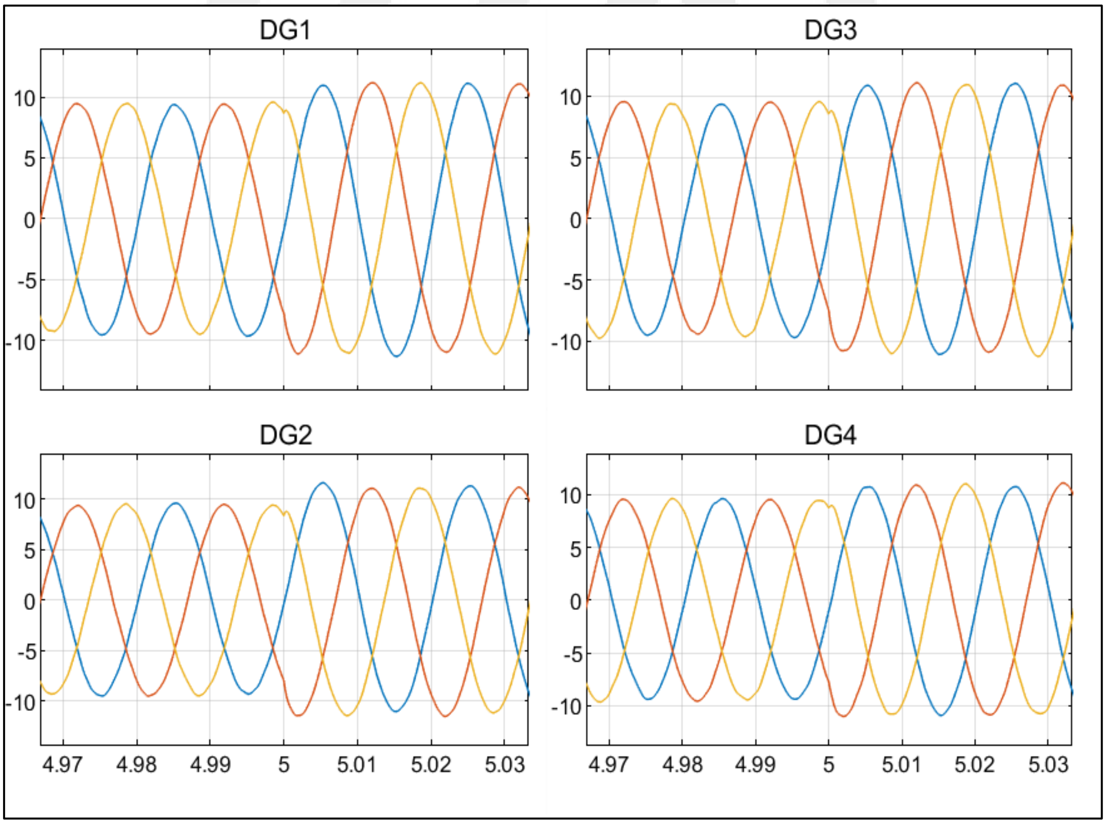

Figure 4.6: DG Currents under CFGSA-DO Control.

The results demonstrate that the CFGSA-DO mitigated V-f deviations before, during, and after adding load 2. Under optimization, V_j deviation is maintained at 0.4V, and the restoration time is less than 0.01s. Concerning P-f regulation, CFGSA-DO causes significant reduction in the frequency deviation (0.0002), load addition at t = 5s, and after load isolation at t = 10s. This reduction is compared to the P-f in [165], where the deviation decreases from 0.006 to 0.00025 while maintaining the same convergence time (1.5s). Figures 4.5 and 4.6 depict three-phase voltage and current response waves for this scenario. Below, remarks of figures 4.1, 4.2, 4.3, and 4.4: CFGSA-DO vs. PSO model predictive control comparison:

a. APS under PSO-optimized droop (Figure 4.1):

i. Observations: APS contributing to enhanced frequency stability.

b. RPS under PSO-optimized droop (Figure 4.2):

i. Observations: The response of PSO-optimized droop on RPS.

c. APS under CFGSA-DO control (Figure 4.3):

i. Observations: Shows the effectiveness of CFGSA-DO in managing APS.

ii. Implications: CFGSA-DO maintains APS and reduces fluctuation during disturbance.

d. RPS under CFGSA-DO control (Figure 4.4):

i. Observations: Illustrates the impact of CF-GSA-optimized droop on RPS.

ii. Implications: CFGSA-DO response of RPS, minimizing V_j flectiuation.

The remarks Figures 4.5 and 4.6: DG voltages and currents:

a. The remarks of DG Voltages under CFGSA-DO control (Figure 4.5):

i. Observations: Indicates the impact of optimization in minimizing V_j flectiuation

ii. Implications: The CFGSA-DO maintains stable V_j minimizing its fluctuation

b. The remarks of DG Currents under CFGSA-DO control (Figure 4.6):

i. Observations: Shows the influence of optimization on DG currents.

ii. Implications: The proposed optimization stabilized DG currents during disturbance.

4.2 DISTRIBUTED GENERATOR TRIP UNDER LOAD VARIATION

A sudden trip of a DG require robust control to absorb the disturbance and implement a redistribution of Q among other DGs. This case is designed to pose a worst scenario case by adding unexpected inductive load. This disturbance in load sharing causes huge V-f fluctuations. The optimized control must ensure that remaining DGs compensate for the loss, preventing V-f deviations, protecting the sensitive loads. CFGSA-DO managed to enhance inductive load sharing resilience during DG trips since it contain rapid adjustments in droop parameters to optimize its instantaneous performance based finding the optimal solutions momentarily during the disturbance.

In these results, CFGSA-DO demonstrates effective response in compensating for generation shortage, offsetting the energy demand requirements caused by DG tripping at t = 5s. This fast response managed to minimize disturbances on each bus, preventing potential failures due to excessive V-f deviations.

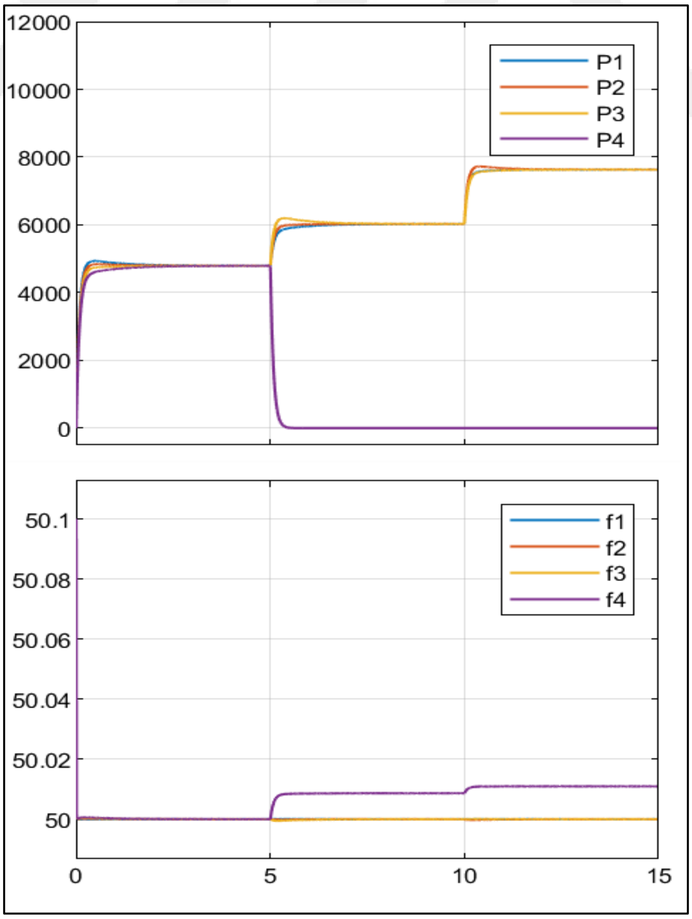

Figure 4.7: APS Response of CFGSA-DO Control, DG Trip at t = 5s Then Adding Load at t = 10s.

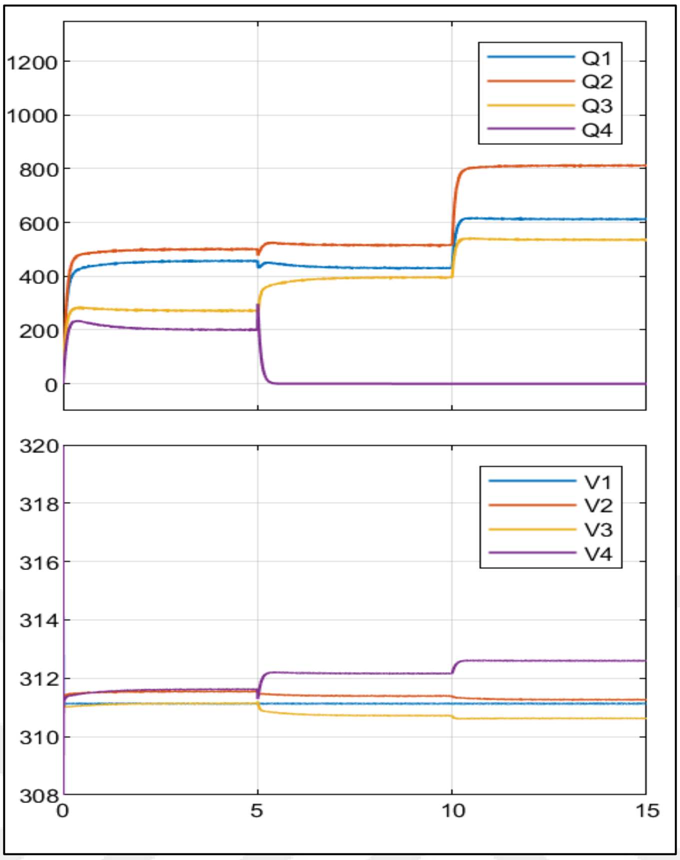

Figure 4.8: RPS Response of CFGSA-DO Control, DG Trip at t = 5s Then Adding Load at t = 10s.

Figures 4.7 and 4.8 depict the robust and adaptable response of CFGSA-DO. Even after DG4 disconnection at t = 5s, other DGs compensate for the power shortage and after additional inductive load (load 2) is connected at t = 10s. Due to the line impedances in the radial MG connection, DG3, the nearest source to the tripped DG, experiences the highest pressure among other DGs.

The remarks of figure 4.7: APS response of CFGSA-DO:

a. DG Trip at t = 5s:

i. The results demonstrates CFGSA-DO response to a sudden trip or DG failure at t = 5s.

ii. Fast compensation minimizes disturbances on PCC, preventing potential failures.

b. Inductive Load Addition at t = 10s:

i. Shows adaptability to cope with additional inductive load 2 connected at t = 10s.

ii. DGs compensate for generation shortage caused by DG4 disconnection.

The remarks of figure 4.8: RPS response of CFGSA-DO:

a. DG Trip at t = 5s:

i. It illustrates the robustness of CFGSA-DO after DG4 disconnection at t = 5s.

ii. Other DGs compensate, preventing disruptions. DG3 experiences a temporary V_j drop of an acceptable 0.4V.

b. Inductive Load Addition at t = 10s:

i. The response demonstrates the adaptability of DG4 to the new load.

ii. DG4's no-load V-f increases by 0.7V and 0.01 Hz post t = 5s.

iii. Load 4 operates without transient fluctuations

4.3 SECONDARY CONTROL FAILURE CASE

SC layer failures due to communication delays cause serious challenges. The communication failure due to communication delays disrupts the exchange of information in MG regarding load conditions and DGs. This can lead to supply-demand imbalances, leading to deviations from desired V-f levels. These deviations can affect connected loads. In MG, PS control is crucial for maintaining voltage levels. This section also looks at these challenges and how CFGSA-DO overcome its effects.

Also, a general methodology of MG control is modeled. Therefore, the proposed system is subjected to a challenging scenario involving a SC failure. Instead of the previous all-to-all mesh topology, a simplified daisy chain topology is employed. This topology, characterized by poor connectivity, lacks the robustness to handle congestion and communication delays, thereby damaging proper information exchange. Also, SC layer of each DG is restricted to communicating with its adjacent DGs within this graph structure as shown in the adjacency matrix (A) which is [4×4], where all aij weight values are considered one.

$$A = \begin{bmatrix} 0 & a_{12} & 0 & 0 \\ a_{21} & 0 & a_{23} & 0 \\ 0 & a_{32} & 0 & a_{34} \\ 0 & 0 & a_{43} & 0 \end{bmatrix} \tag{4.1}$$

This matrix depict the connectivity of all nodes in the graph. To induce a significant failure in SC, a communication delay of 50ms is applied to each communication link. The system loads on buses 1, 3, and 4 are connected while load 2 is added at t = 5s to t = 10s, load 2 is applied to assess the control operation under two complex tasks. The stability of conventional droop controlled MG is compromised due to its limitations, as depicted in Figures 4.9 and 4.10.

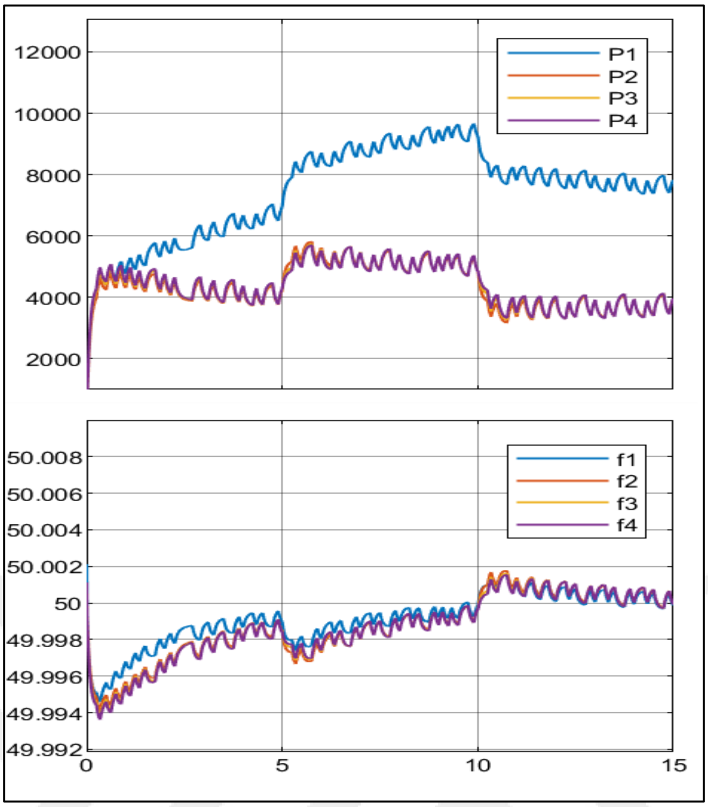

Figure 4.9: APS Response of Conventional Droop Under 0.5s Communication Delay, Daisy-Chain Topology, from T = 5s to T = 10s Load is Added.

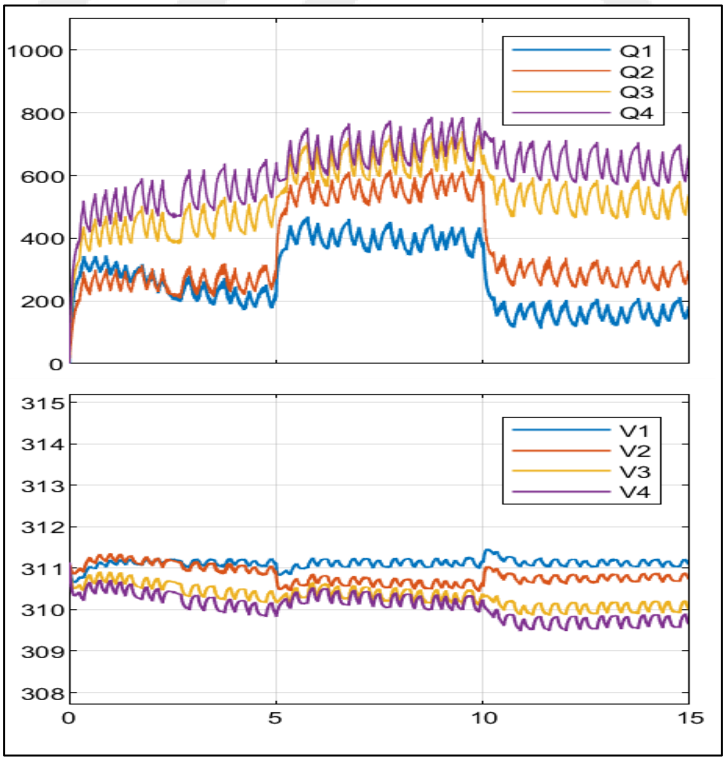

Figure 4.10: RPS Regulation Response of Conventional Droop under 0.5s Communication Delay, Daisy-Chain Topology, from T = 5s To T = 10s Load is Added.

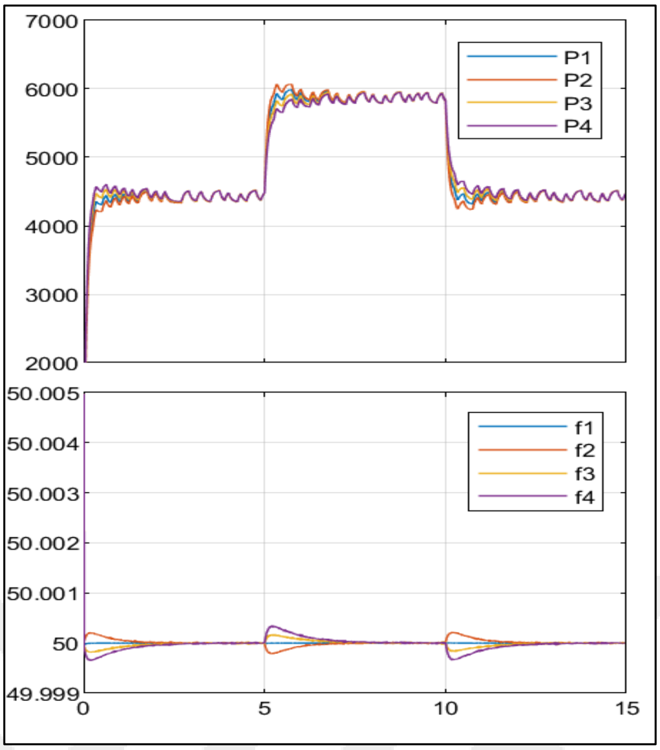

Figure 4.11: APS Response of CFGSA-DO under 0.5s Communication Delay, Daisy-chain Topology, from t = 5s to t = 10s Load is Added.

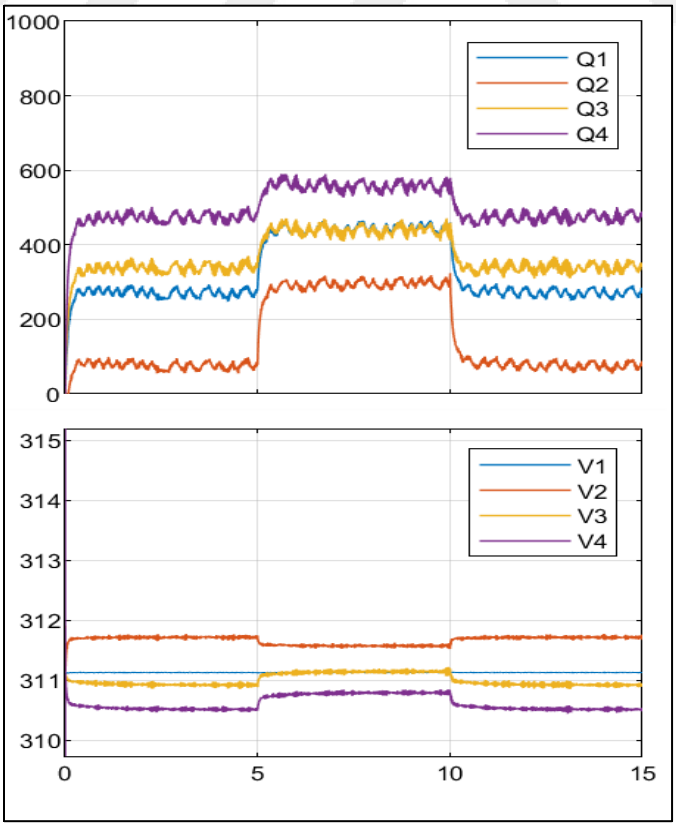

Figure 4.12: RPS Response of CFGSA-DO under 0.5s Communication Delay, Daisy-chain Topology, from T = 5s to T = 10s Load is Added.

However, as illustrated in Figures 4.11 and 4.12, the CFGSA-DO exhibits a response within an acceptable range under daisy-chain topology and communication delay conditions. Low frequency deviations (less than 0.0005 Hz) and V_j fluctuations (less than 0.7 V) are observed, indicating a robustness level close to the normal response achieved under all to al) communication topology.

The remarks of figures 4.9 and 4.10: Conventional Droop control response:

a. APS of conventional droop control (Figure 4.9):

i. Scenario: Daisy chain topology, 0.5s communication delay, adding load from t = 5s to t = 10s.

ii. Observations: inadequate response with unacceptable V-f deviations. The stability of MG is compromised under conventional droop control, impacting APS.

b. RPS of conventional droop control (Figure 4.10):

i. Observations: Unacceptable V-f deviations persist, emphasizing the limitations of conventional droop control in the specified conditions.

The remarks of Figures 4.11 and 4.12 of CFGSA-DO response

a. APS of CFGSA-DO (Figure 4.11):

i. Scenario: Daisy chain topology, 0.5s communication delay, adding load from t = 5s to t = 10s.

ii. Observations: Response within an acceptable range of frequency deviations (less than 0.0005 Hz). CFGSA-DO exhibits improved stability under challenging conditions.

b. RPS of CFGSA-DO (Figure 4.12):

i. Observations: Moderate V_j fluctuations (less than 0.7 V), indicating superior robustness.

5. CONCLUSION AND FUTURE WORK

In this thesis, an optimized droop control optimized through a CF-GSA approach is introduced to enhance power distribution within MG. The MG optimized model comprising four DGs, four buses, and various loads, is interconnected in a radial configuration. The proposed control mechanism is designed to address the complicated and challenging dynamics of MG. PC involves supervising and adjusting four critical parameters (m_p, n_q, K_{pv}, and K_{ic}) under the vigilant guidance of the optimized droop control. Upon development, this optimized control system undergoes testing, subjected to an array of diverse operational scenarios and disturbances. The outcomes of these tests reveal the control system's robustness. CFGSA-DO enhances the PS among DGs, ensuring system stability while regulating V-f levels within MG. To validate CFGSA-DO response, three combined scenarios are investigated. These scenarios involve additional load, instances of SC failure, and disconnection of a DG. Throughout these trials, CFGSA-DO exhibits a rapid and dynamic response, encountering disturbances. It optimizes PS mitigating V-f deviations. The proposal and simulation of a CF-GSA metaheuristic algorithm for efficient PS have been put forth. The necessity for the PS methodologies holds significance in ensuring MGs dependable and consistent operation, given the escalating use and integration of DERs in power grids. Despite its simplicity, the conventional droop control system encounters challenges in sustaining stable MGs with high penetration of RESs. Droop control, a fundamental concept in EMS, has undergone many enhancements. One notable advancement is the optimized droop control. This approach enhances MGs stability ensuring PS better even at varying conditions. The researchers have explored feedback control, allowing for more development crucial for voltage stabilization within MG. The traditional droop methods have challenges in load sharing, many works failed to solve this obstacle. Therefore, analytical evaluations of CFGSA-DO have been conducted in autonomous MGs, emphasizing its pivotal role in PS. There are three cases used to test CFGSA-DO response:

a. Load Fluctuations (Case 1): CFGSA-DO managed the dynamic changes in load demand within MG. The results, as depicted in the last chapter, show a precise V-f regulation, mitigating deviations to a significant extent. The reduction in V-f deviations underscores CFGSA-DO robustness. This reduction not only ensures stable MG operation but also validates the efficacy of the scheme in adapting to varying MG dynamics. There has been a rapid restoration time achieved by the proposed optimizer, less than 0.01 seconds.

b. Sudden Disconnection of a DG (Case 2): A sudden DG disconnection, CFGSA-DO demonstrated an efficiency to prevent power shortage impacts to ensure the stability of MGs. Also, while additional inductive load is added, MG maintained stability of complex disturbances.
c. SC Control Failure (Case 3): There has been a resilience in mitigating SC failure induced by communication delays. CFGSA-DO proved instrumental in maintaining stability despite daisy chain topology limited connectivity. CFGSA-DO response remained within tolerated ranges. This adaptability is a significant to mitigate critical issues associated with SC failure.

5.1 CHAPTER SUMMARY

a. Chapter 1 provided an overview of MG control, literature survey of recent studies and optimization applications in power systems, highlighting literature behind the research presented in this thesis, outlining the details, limitations, complications, and challenges encountered in MG design and control.
b. Chapter 2 has covered the foundational theoretical framework of MGs which has been discussed, including the pertinent electrical equations. The chapter described the core concepts of graph theory and provided an in-depth explanation of the functioning of MG control. The chapter also offered a concise comparison of various MG control techniques.
c. Chapter 3 explained MG modeling and outlined the functioning of CFGSA-DO. The chapter highlighted common challenges of MGs modeling and discussed the math modelling and assumptions made to simulate MG, aligning the models with practical scenarios.
d. Chapter 4 presented simulation case studies and explored communication topologies and delays, involving scenarios such as the base case, where no communication occurred between distributed generators, and the fault case, simulating a scenario where one generator tripped. Also, a sensitivity analysis has been conducted, and the chapter concluded by discussing the response of CFGSA-DO control across these various situations.

5.2 CONTRIBUTIONS OF THESIS

They is highlighted as following:

a. The efficiency, ease of implementation, and cost-effectiveness of CFGSA-DO control have been demonstrated. All the involved generators converge to the intended Q value after a load disturbance, maintaining all PCC voltages within the specified range.
b. In this thesis study, the pivotal role of communication topology among distributed generators in CFGSA-DO control response has been substantiated. Achieving the quickest response necessitated the highest level of connectivity among the generators. the convergence of time among the communication topologies examined in this research has been evident. Among these, the looped topology exhibited the fast response, establishing itself as the most efficient communication network.
c. The simulation of CFGSA-DO control under varying communication delays underscored the importance of an appropriate and dependable communication channel system. It has been demonstrated that a communication system led to quicker convergence, necessitating the requirement for an optimal communication channel. Enhanced communication channels facilitated rapid data exchange among the distributed generators, thereby accelerating the total convergence process of all generators.
d. The fault scenario, involving the trip of any generator, has been investigated. Despite CFGSA-DO control response decline in the event of a generator trip, it has been demonstrated that system stability could be maintained through straightforward control measures, such as opening PCC-ties using interlocks. Although this action removes generators from CFGSA-DO control, compelling MGs into islanding mode, it ensures total system stability, preventing any V_j fluctuations, a concern for end consumers.
e. Sensitivity analysis of CFGSA-DO control has been conducted in this study. The research demonstrated that variations in generation influence the convergence rate CFGSA-DO. Hence, meticulous tuning of DG droop parameters is crucial for achieving an optimal convergence, avoiding V-f oscillations. In addition to droop analysis.

5.3 FUTURE WORK

In future research, the inclusion of MGCs droop optimization needs a more complex analysis, involving factors such as inertial loads and frequency variations in multiple MGs. The study is incorporate MGC modeling of power electronic inverters and DGs, addressing associated challenges such as control issues, harmonics, reliability, and communication complexities to share information among DGs in different MGs interconnected in a cluster. Considering that MGCs often consist of MGs and DGs with varying sizes and ratings, other scenarios worth exploring involves a situation where one DG operates at maximum power capacity, leading to saturation. In such a case, this generator is fixed at its maximum output dispatch, while the remaining DGs share the remaining power load. Furthermore, it's essential to conduct fault analysis within MGC control scheme. Since the DGs operate on feedback control, there is a theoretical risk of increased fault levels. Therefore, the protection system has to be coordinated, investigated, and designed to withstand and isolate any faults avoiding significant damage.

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APPENDIX A

MATLAB SIMULINK OF MICROGRID CONTROL

It has three levels: primary (droop) control, SC, and tertiary control.

A.1 PRIMARY CONTROL

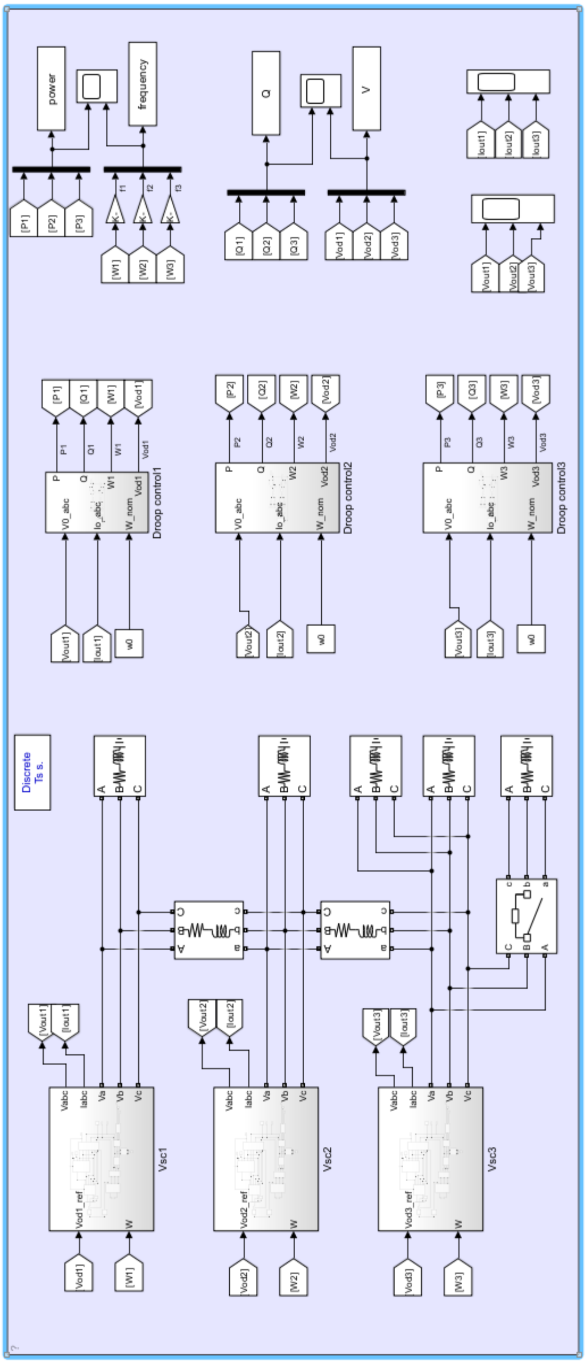

Figure A.1: Simulink Diagram of MG Controlled by Primary Droop Control.

A.2 SECONDARY CONTROL

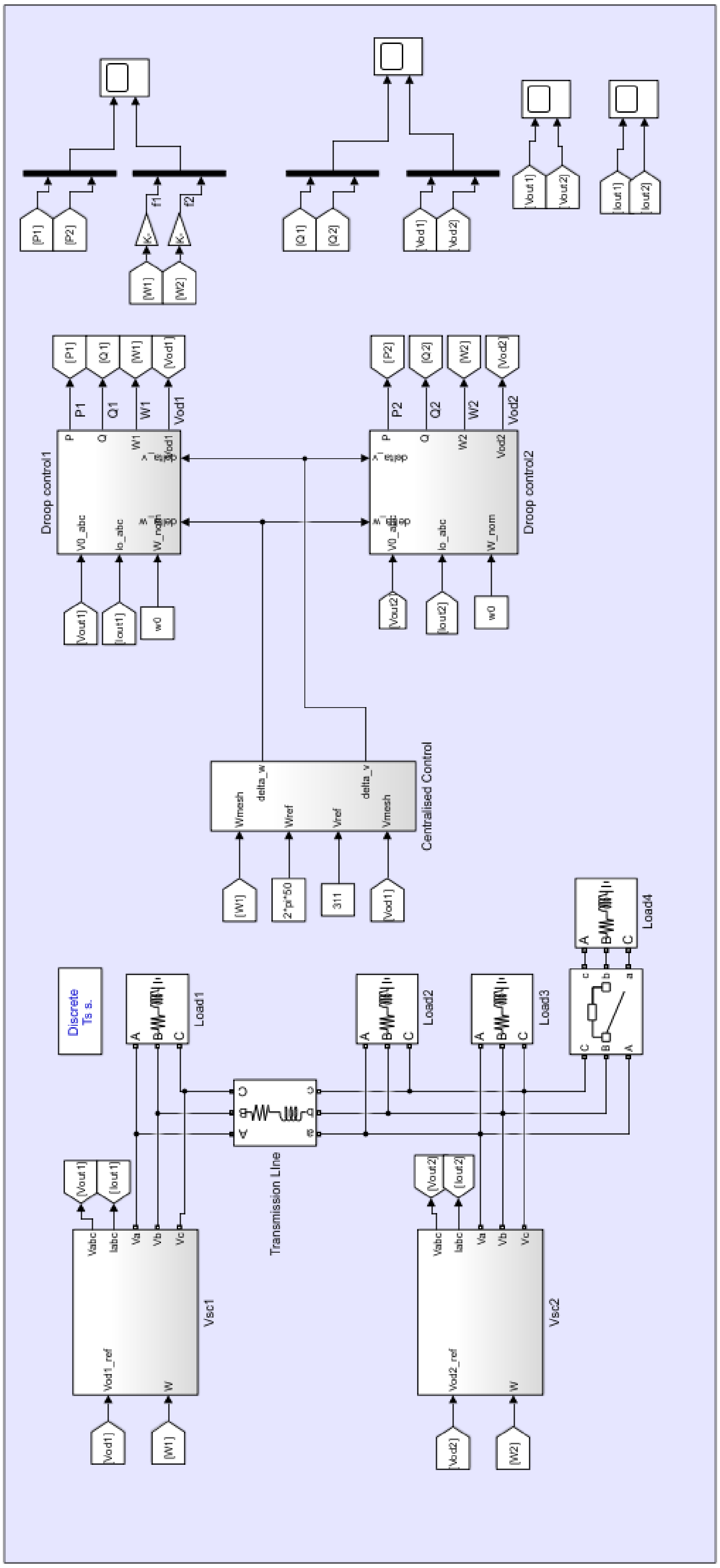

Figure A.2: Simulink Diagram of MG with SC

A.3 OPTIMIZED DROOP CONTROL

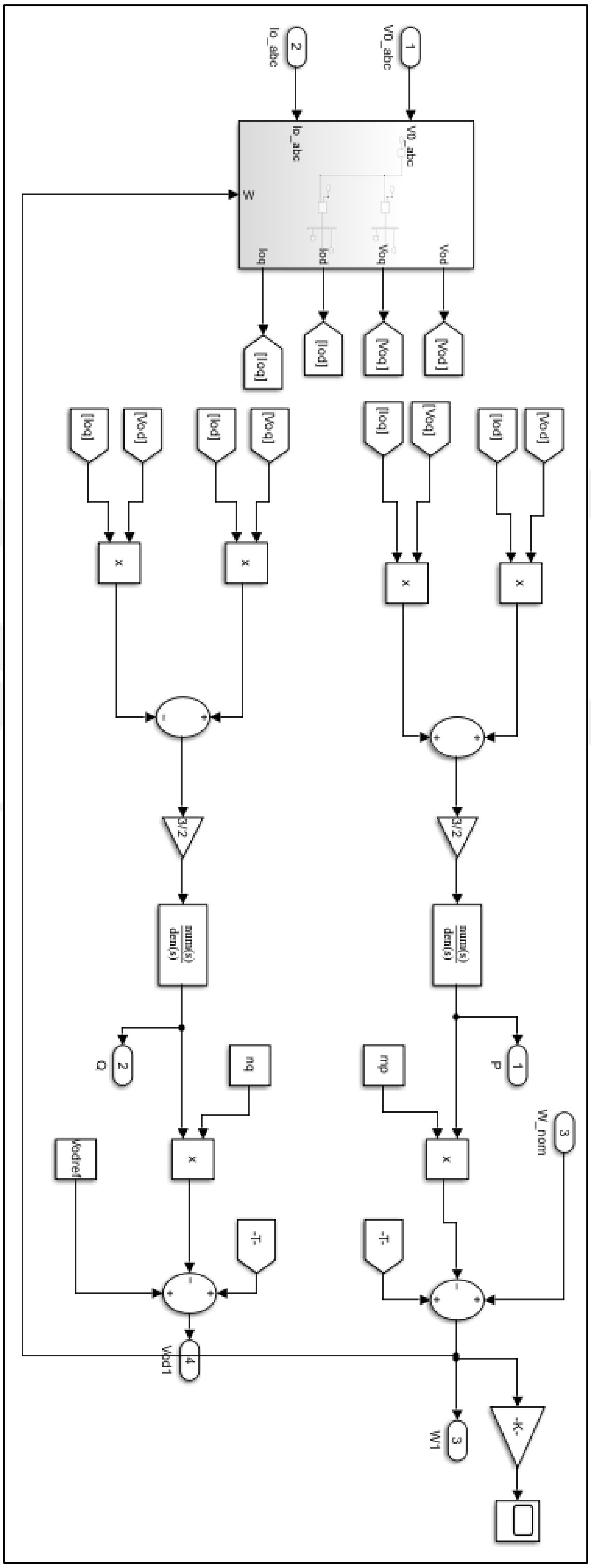

Figure A.3: Simulink Diagram of Droop Control Loop

A.4 MICROGRID CENTRALIZED CONTROL SYSTEM

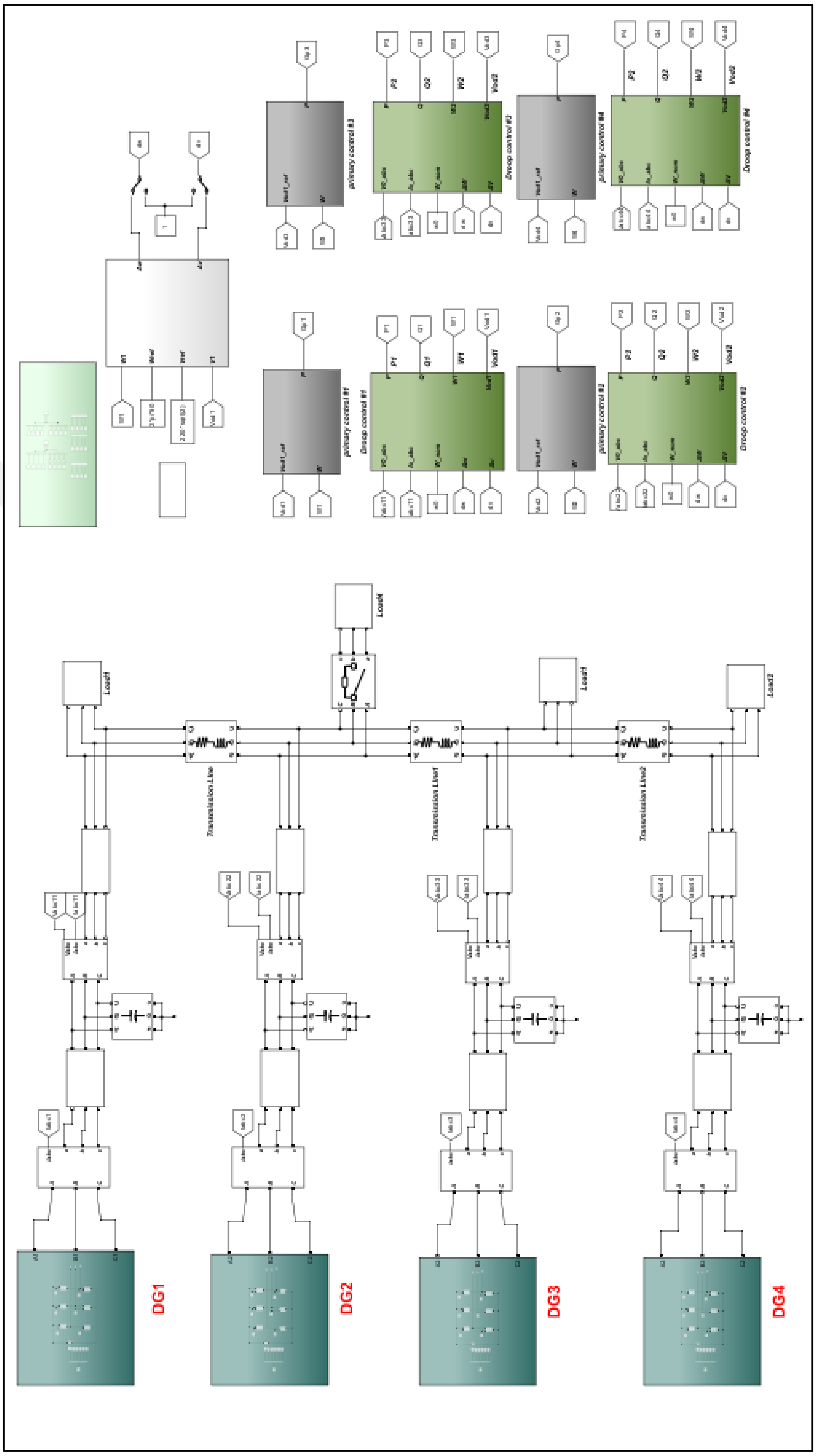

Figure A.4: Simulink Diagram of MG Centralized Control System

A.5 MICROGRID DISTRIBUTED CONTROL SYSTEM

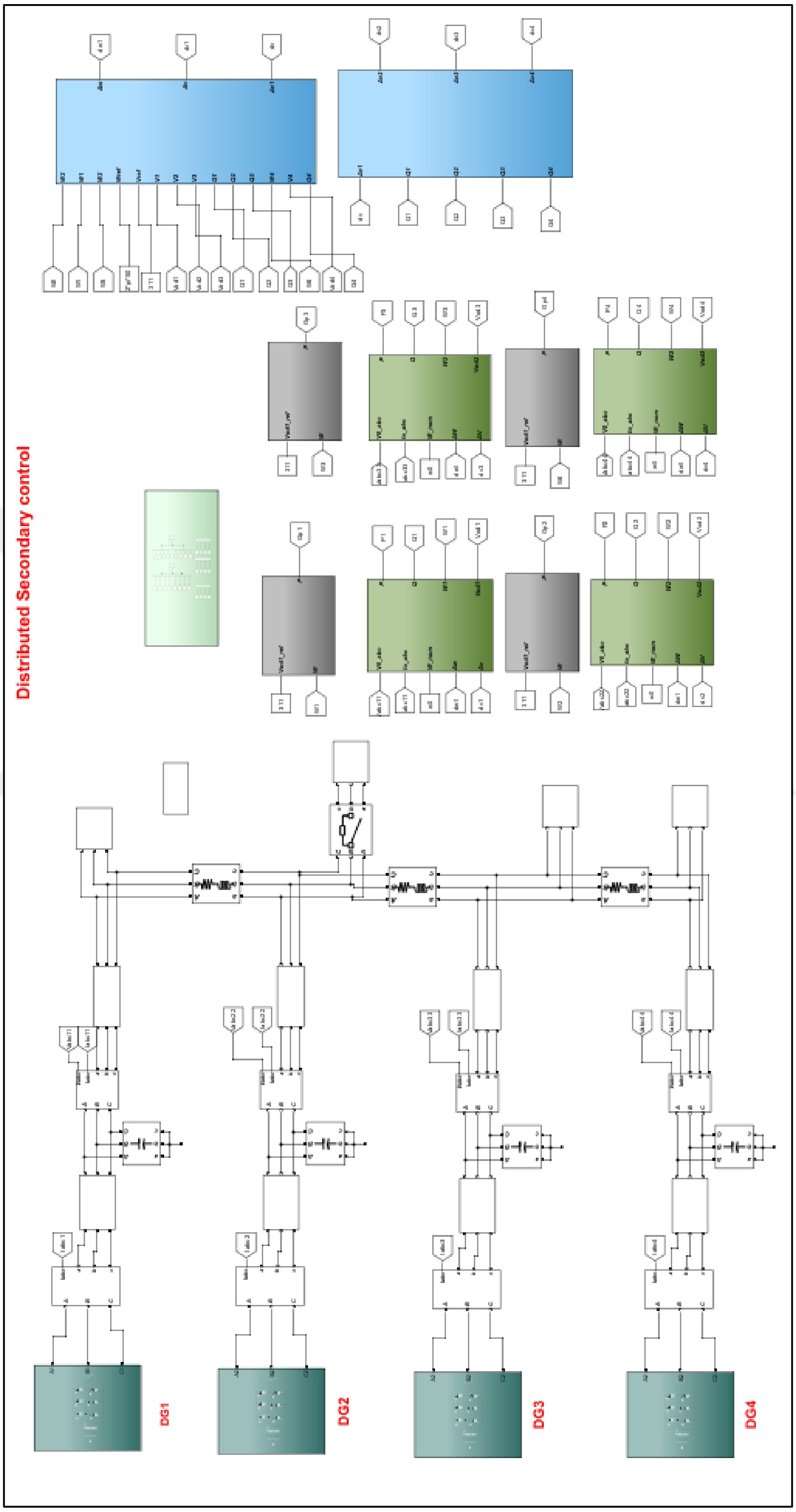

Figure A.5: Simulink Diagram of MG Distributed Control System