RESSALVA

Atendendo solicitação do(a) autor(a) o texto completo desta Dissertação será disponibilizado somente a partir de 21/09/2023.

Augusto Matheus dos Santos Alonso

Multi-Purpose Coordinated Control of Distributed Energy Resources in Transactive AC Microgrids

Thesis for the degree of Philosophiae Doctor

(Under a Cotutelle Agreement Between NTNU and UNESP)

September 2021

Norwegian University of Science and Technology (NTNU)
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

São Paulo State University (UNESP)
School of Engineering
Campus of Bauru - Brazil

Supervisor: Fernando Pinhabel Marafão - UNESP/Sorocaba-Brazil
Supervisor: Elisabetta Tedeschi - NTNU/Trondheim-Norway
Co-supervisor: Danilo Iglesias Brandão - UFMG/Belo Horizonte-Brazil

A454m

Alonso, Augusto Matheus dos Santos
Multi-Purpose Coordinated Control of Distributed Energy Resources in Transactive AC Microgrids / Augusto Matheus dos Santos Alonso. -- Bauru, 2021
252 p. : il., tabs., fotos

Tese (doutorado) - Universidade Estadual Paulista (Unesp), Faculdade de Engenharia, Bauru
Orientador: Fernando Pinhabel Marafão
Coorientador: Danilo Iglesias Brandão

1. controle coordenado. 2. inversores. 3. microrredes. 4. qualidade da energia. 5. recursos energéticos distribuídos. I. Título.

Sistema de geração automática de fichas catalográficas da Unesp. Biblioteca da Faculdade de Engenharia, Bauru. Dados fornecidos pelo autor(a).

Essa ficha não pode ser modificada.

RECORD OF THE PUBLIC DEFENSE OF THE DOCTORAL THESIS BY AUGUSTO MATHEUS DOS SANTOS ALONSO, PhD CANDIDATE OF THE GRADUATE PROGRAM OF ELECTRICAL ENGINEERING AT THE SCHOOL OF ENGINEERING, CAMPUS OF BAURU.

On the 22nd of September 2021, at 8:00 am, the public defense of the DOCTORAL THESIS entitled as **MULTI-PURPOSE COORDINATED CONTROL OF DISTRIBUTED ENERGY RESOURCES IN TRANSACTIVE AC MICROGRIDS,** by AUGUSTO MATHEUS DOS SANTOS ALONSO, was carried out remotely (by video conference). The Evaluation Committee was constituted by Prof. Dr. GILBERT BERGNA-DIAZ (Chairperson - Virtual Participation) from the Department of Electric Power Engineering / NTNU, Prof. Dr. SIMONE BUSO (Virtual Participation) from the Department of Information Engineering / University of Padova, Prof. Dr. JOHAN DRIESEN (Virtual Participation) from the Department of Electrical Engineering (ESAT-ELECTA) / KU Leuven, Profª. Drª. BIRGITTE BAK-JENSEN (Virtual Participation) from the AAU Energy / Aalborg University, Prof. Dr. RICARDO QUADROS MACHADO (Virtual Participation) from the Department of Electrical Engineering / University of São Paulo – Campus São Carlos. After the presentation by the PhD candidate and the examination by the Evaluation Committee members, the candidate received the final concept of **APPROVED**. Finally, this record was drawn-up, being later read, approved and signed by the Evaluation Committee chairperson.

Gilbert Bergna Diaz

Prof. Dr. GILBERT BERGNA-DIAZ

I dedicate this PhD thesis to my parents, Dirce and Mauro, for their endless support, which has allowed me to pursue my dreams so far in life.

Eu dedico esta tese de doutorado aos meus pais, Dirce e Mauro, por seu suporte infindável, o qual me possibilitou ir em busca de meus sonhos até aqui.

Abstract

Pervasive penetration of distributed energy resources (DERs), usually constituted by renewable energy sources and/or storage systems along with their interfacing inverters, are pushing AC electrical grids toward a power electronics-based paradigm. Although the presence of DERs in power grids brings more flexibility of operation and the decentralization of energy generation allows us to obtain more efficient power dispatch, it is imperative to achieve proper control over the existing inverters to support the synergistic integration of multiple electric apparatuses. This is particularly true from the perspective of inverter-dominated AC microgrids (MGs), which rely on the implementation of coordination strategies to adequately exploit DERs to support controlled power dispatchability, power quality interventions, as well as accessibility to energy markets.

Within such a context, this thesis presents a coordinated control strategy capable of supporting multiple operation modes for transactive AC MGs through a model-free, plug-and-play and topology-independent steering of inverters. Such a control approach, namely Generalized Current-Based Control (GCBC), is capable of accommodating inverters of assorted operational natures, being of a dispatchable (d-DER) or non-dispatchable (nd-DER) nature, relying on a centralized unit and on low-bandwidth communication links. By flexibly coordinating DERs, the strategy supports the implementation of active current sharing among inverters, also endowing compensation of reactive currents, as well as offering distributed and selective harmonic mitigation. In addition, the control approach is capable of coping with intermittent energy generation profiles, which are typical of nd-DERs. As another feature, the proposed coordination strategy provides proportional current sharing without being affected by line impedance parameters, in contrast to the conventional droop control method. Above all, the GCBC strategy is capable of managing an interconnected MG to operate as a single controllable entity, providing full controllability over its power dispatch to an upstream grid, allowing it to trade energy services in transactive energy markets.

The merits of the GCBC strategy are thoroughly assessed throughout this thesis by means of simulation and experimental results, based on multiple MG prototypes focusing on the low-voltage (LV) perspective, ensuring that the method is feasible for implementation in real-life applications. Numerous MG scenarios are evaluated, such as under limited power capabilities, considering the presence of non-ideal voltage waveforms, as well as upon communication issues, ensuring that the GCBC approach endures operation under adverse conditions. Moreover, it is experimentally demonstrated that the method is also capable of improving voltage quality in weak LV MGs

of homogeneous features, as an indirect outcome of the proportional sharing of non-active currents.

Lastly, advanced control functionalities are devised by flexibly adapting the GCBC strategy, endowing LV MGs with the capacity to shape their operation to behave as a variable and selective resistor, which supports a more efficient operation of the distribution grid and favors the damping of harmonic resonances. As another advanced functionality, distributed compensation of active and reactive unbalanced currents is also possible, based on concepts from the Conservative Power Theory. Moreover, voltage regulation can be ensured for the MG by means of an automatic scheme incorporating the GCBC, allowing the possibility to concomitantly increase energy exploitation from nd-DERs. Finally, considerations on the integration of optimization methods highlight that further capabilities can be formulated upon the adoption of the GCBC strategy.

Sammendrag

En omfattende integrasjon av distribuerte energikilder (DERer), som består av fornybare energisystemer med tilhørende omformere, representerer et paradigmeskifte for AC strømnett i form av økt bruk av kraftelektronikk. Selv om bruken av DERer i lavspenningsnettet muliggjør en mer fleksibel drift av nettet, og desentralisering av energikildene tillater en økt effektivitet, er det helt avgjørende å ha tilstrekkelig kontroll over eksisterende omformere for å utnytte potensialet i dem. Dette gjelder særlig for omformerdominerte mikronett, som er avhengige implementering av koordinerte strategier for å utnytte DERer til kontrollert kraftregulering, forbedring av spenningskvalitet, samt tilgjengelighet til elektrisitetsmarkedet.

Denne avhandlingen presenterer en koordinert reguleringsstrategi for mikronett. Strategien kan levere flere systemtjenester, og reguleringen legger til rette for plug-and-play av omformere, uavhengig av topologien til nettet. Denne strategien, kalt Generalized Current-Based Control (GCBC), kan integrere omformere basert på både regulerbare (d-DER) og ikke-regulerbare (nd-DER) energikilder. Strategien er avhengig av en sentralisert kontrollenhet samt et kommunikasjonssystem med lav båndbredde. Ved hjelp av fleksibel koordinering av DERer støtter strategien deling av aktive strømmer mellom omformere, kompensasjon av reaktive strømmer, samt tilbyr distribuert og selektiv harmonisk demping. I tillegg kan strategien håndtere intermitterende energiproduksjonsprofiler, som er typiske for nd-DERer. I motsetning til den konvensjonelle statikk-metoden er den foreslåtte strategien også i stand til å gi proporsjonal strømdeling uten å være påvirket av linjeimpedansparametere. Fremfor alt er GCBC-strategien i stand til å styre et sammenkoblet mikronett for å fungere som én enkelt kontrollerbar enhet, samt å ha full kontrollerbarhet over kraftutvekslingen med et overliggende nett, slik at mikronettet kan handle energitjenester i bilaterale energimarkeder.

Aspektene ved GCBC-strategien blir grundig gjennomgått i denne avhandlingen ved hjelp av simulering og eksperimentelle resultater, basert på flere lavspente (LV) mikronett-prototyper, for å sikre at metoden er mulig å implementere i ekte applikasjoner. Flere mikronett-scenarier blir evaluert, for eksempel ved begrenset effekt, under ikke-ideelle spenningsforhold, samt ved kommunikasjonsproblemer. Dette sikrer at GCBC-strategien fungerer også under ugunstige forhold. Videre er det eksperimentelt demonstrert at metoden er i stand til å forbedre spenningskvaliteten i svake LV mikronett, noe som er et indirekte resultat av proporsjonal deling av ikke-aktive strømmer.

Til slutt utvikles avanserte kontrollfunksjoner ved fleksibel tilpasning av GCBC-strategien, hvilket gir LV mikronett muligheten til å oppføre seg som en variabel og selektiv motstand, som støtter en mer effektiv drift av distribusjonsnettet og bidrar til

demping av harmoniske resonanser. En annen avansert funksjonalitet er distribuert kompensasjon av aktive og reaktive ubalanserte strømmer, basert på konsepter fra «Conservative Power Theory». Videre kan spenningsregulering utformes for mikronettet ved hjelp av en strategi som inkluderer GCBC, slik at man samtidig kan øke energiutnyttelsen fra nd-DERer. Betraktninger rundt integrering av optimaliseringsmetoder fremhever at ytterligere funksjonalitet fortsatt kan legges til ved bruk av GCBC-strategien.

Resumo

A contínua expansão do uso de recursos energéticos distribuídos (REDs), normalmente constituídos de fontes de energia renovável e/ou sistemas de armazenamento com seus respectivos inversores de potência, tem incorporado a eletrônica em potência como panorama para redes elétricas CA. Embora a presença de REDs em tais redes traga maior flexibilidade de operação e a descentralização da geração de energia possibilite despacho de potência mais eficiente, é essencial que se imponha um controle adequado sob inversores para garantir uma operação harmoniosa com os múltiplos dispositivos elétricos existentes. Tal requerimento é de particular importância em microrredes CA com alta imersão de inversores, as quais requerem a implementação de estratégias de controle coordenado para adequadamente explorar REDs, visando obter controlabilidade perante despacho de potência, intervenções para melhoria da qualidade da energia, e também acessibilidade a mercados de energia.

Dentro de tal contexto, esta tese de doutorado apresenta uma estratégia de controle coordenado capaz de prover múltiplos propósitos operacionais para microrredes CA com características transativas. Tal abordagem rege a operação de inversores sem necessitar conhecimento prévio das características da microrrede, independentemente da topologia elétrica, e ofertando operacionalidades *plug-and-play*. Esta estratégia, nomeada *Generalized Current-Based Control* (GCBC), é capaz de acomodar inversores de características diversas, sendo de natureza despachável (d-RED) ou não-despachável (nd-RED), com base em uma unidade centralizadora e em canais de comunicação de banda estreita. Através da coordenação flexível de REDs, a estratégia suporta a implementação de compartilhamento de correntes ativas, tão bem quanto a compensação de correntes reativas, além da mitigação distribuída e seletiva de harmônicos. Ademais, a estratégia de controle é complacente com perfis intermitentes de geração de energia, os quais são comuns em nd-REDs. Além disso, outra vantagem se refere à capacidade de prover compartilhamento de correntes entre inversores de forma proporcional às suas capacidades, sem interferência das características de impedâncias de linha, diferente do método convencional de controle *droop* (i.e., controle por inclinação). Acima de tudo, a estratégia GCBC é capaz de gerenciar uma microrrede CA interconectada para operar como uma entidade única controlável, provendo controlabilidade total sob seu despacho de potência para a rede de distribuição, permitindo a negociação de serviços energéticos em mercados de energia transativos.

Os méritos da estratégia GCBC são amplamente avaliados ao longo desta tese, por meio de simulação e resultados experimentais, com base em múltiplos protótipos

de microrrede com foco em baixa tensão, garantindo que o método é viável a implementações práticas reais. Diversos cenários de microrrede são analisados, tal como sob limitação de capacidades de potência, considerando a presença de tensões não ideias, e também perante complicações relacionadas à comunicação de dados, certificando que a estratégia GCBC é capaz de operar sob condições adversas. Ainda, demonstra-se através de resultados experimentais que o método de controle é capaz de prover melhoria da qualidade da tensão em microrredes fracas de baixa tensão que apresentam características homogêneas, como um resultado indireto do compartilhamento proporcional de correntes não ativas.

Finalmente, funcionalidades de controle avançadas são flexivelmente derivadas com base na abordagem GCBC, possibilitando que uma microrrede seja capaz de modelar sua operação para se comportar como um resistor variável e seletivo, o qual suporta uma operação mais eficiente da rede de distribuição, ainda favorecendo o amortecimento de ressonâncias harmônicas. Como outra funcionalidade avançada, compensação distribuída de correntes ativa e reativa de desbalanço pode ser também ofertada, com base em conceitos advindos da Teoria de Potência Conservativa. Ademais, regulação de tensão pode ser implementada para microrredes, com base em um esquema de controle automático incorporando a estratégia GCBC, possibilitando ainda uma exploração de energia aprimorada para nd-REDs. Por último, considerações sob a integração de métodos de otimização também ressaltam que funcionalidades adicionais podem ser formuladas com base na adoção da estratégia GCBC.

Ackowledgements

Above all, I would to thank God, for giving me the strength to overcome the difficult times endured during the period of this PhD project.

I thank my parents, Mauro and Dirce, and my brothers, Lucas and Felype, for supporting and motivating me at all times. It is also impossible to write any acknowledgements without thanking my future wife, Mariana, for her love and tender company throughout all these years.

Most of my time working on this PhD project was spent at UNESP/Sorocaba-Brazil, and I thank all my colleagues for the talks, and the company during the many days and nights spent in the lab. A particular thanks goes to Wesley A. Souza, Eduardo V. Liberado, Luis A. O. Arenas, Rubens T. Hock Jr., Marcelo N. Tirolli, and José A. O. Filho. Moreover, I am grateful to the professors from the *Group of Automation and Integrated Systems (GASI)* at UNESP, particularly to Flávio A. S. Gonçalves and Helmo K. M. Paredes, for their technical support and teaching during the courses I undertook in Brazil.

I also had the pleasure of spending some time at NTNU/Trondheim-Norway, and to participate as a member in the *Power Electronic Systems and Components (PESC)* group. This period was very fruitful from both personal and professional perspectives, and I foremost thank my friends Andreas Giannakis, Erick F. Alves and Spyridon Chapaloglou, who also represent many other amazing people that I was luckily able to meet. I also thank Fredrik T. B. W. Göthner for the technical interaction during the conference paper C.2., as well as for helping me out with the *Sammendrag* of this thesis. From the staff side, I thank Bodil V. Wold and Åshild U. Meistad for making my stay at NTNU more pleasant. Lastly, I thank Santiago S. Acevedo and Salvatore D'Arco, from *SINTEF Energy*, for supporting me on my short experience at the *National Smart Grid Laboratory*.

I am very grateful to the *São Paulo Research Foundation (FAPESP)*, for the grant 2017/24652-8, which provided me with financial support for this PhD project, as well as for the grant 2018/22172-1 that allowed me to develop part of my research at NTNU. I also thank FAPESP for the grant 2016/08645-9, since this thesis is incorporated into a larger thematic project. To conclude, I thank the *Research Council of Norway*, since my Cotutelle agreement is a direct outcome of the cooperation between UNESP and NTNU, which was initiated with the *NB_POCCREI* project (grant f261735/H30).

I thank the evaluation committee of my mid-term (qualifying) examination, Prof.

Josep M. Guerrero from Aalborg University, Prof. Mohammad Amin from NTNU, and Prof. Pericle Zanchetta from University of Nottingham, for their insightful comments on my project, which oriented me to direct toward completion.

I am lucky to have had three amazing professors guiding me throughout the journey of this PhD project. First, I deeply thank my co-supervisor, Prof. Danilo I. Brandão, for the intensive support given on technical aspects comprised within this project, whenever I needed it. He was fundamental to all the achievements related to this project.

From the NTNU side, I am very thankful for having Prof. Elisabetta Tedeschi as my main supervisor. It has been an enormous pleasure to learn from her during the course I undertook at NTNU, and I thank her for technically supporting me along the entire duration of this project. Especially, I express my appreciation for her, as she always provided me with access to whatever was needed for my project, as well as for making my stay in Norway an unforgettable experience.

Last, but not least, I must thank my main supervisor at UNESP, Prof. Fernando P. Marafão, for conducting me throughout the most challenging and fruitful professional times of my life. I will be ever grateful to him, not only for the technical guidance throughout my master and PhD degrees, but also for giving me opportunity to pursue my professional dreams. I owe to him most of the (limited) technical knowledge I have attained during the last few years.

Contents

List of Tables

List of Figures

List of Acronyms and Abbreviations

AC	Alternating Current
APC	Active Power Curtailment
AVG	Average
CB	Circuit Breaker
CCM	Current Controlled Mode
CPT	Conservative Power Theory
D	CPT's Distortion Power
d-DER	Dispatchable DER
DC	Direct Current
DER	Distributed Energy Resource
DFT	Discrete Fourier Transform
DRA	Demand Response Aggregator
DSO	Distribution System Operator
DSP	Digital Signal Processor
DST	Distribution System Transformer
ESS	Energy Storage System
GCBC	Generalized Current-Based Control
ICT	Information and Communication Technology
LC	Inductive and Capacitive Output Filter
LCL	Inductive-Capacitive-Inductive Output Filter
LPF	Low-Pass Filter
LV	Low-Voltage

MAF Moving Average Filter

MG Microgrid

MG-TES Microgrid Transactive Energy System

MGO Microgrid Operator

N CPT's Unbalance Power from

nd-DER Non-dispatchable DER

P CPT's Active Power

P2P Peer-to-Peer

PCC Point-of-Connection

PF CPT's Power Factor

PLL Phase-Locked-Loop

PoC Point-of-Connection of a DER

PRep Proportional-Repetitive

PRes Proportional-Resonant

Q CPT's Reactive Power

RES Renewable Energy Source

RLS Resistive Load Synthesis

RMS Root Mean Square

SCS Sinusoidal Current Synthesis

SG Smart Grid

SoC State-of-Charge

TES Transactive Energy System

THD_i Total Harmonic Distortion of a Current

THD_v Total Harmonic Distortion of a Voltage

TSO Transmission System Operator

UI Utility Interface

VCM Voltage Controlled Mode

VPP Virtual Power Plant

X/R Ratio Between Inductance and Resistance of Line Impedances

List of Symbols and Variables

$\star$	Refers to the main experimental setup (single-phase MG)
$\dagger$	Refers to the experimental setup from Section 5.8 (three-phase MG)
^{3ph}	Refers to the experimental setup from Section 6.4 (three-phase MG)
$\|\|$	In-phase component
$\perp$	Quadrature component
^{INV}	Refers to the simulation circuit of Section 4.4.2
$\alpha_{h\|\|}$	GCBC in-phase scaling coefficient for harmonic order h
$\alpha_{h\perp}$	GCBC quadrature scaling coefficient for harmonic order h
γ_{Na}	Percentage of compensation for the active unbalanced current parcel
γ_{Nr}	Percentage of compensation for the reactive unbalanced current parcel
γ_{OV}	Activation variable of the active and reactive voltage control
γ_{RLS}	Activation variable of the RLS-based coordination approach
θ_{1m}	Synchronization angle for the fundamental component
θ_{hm}	Synchronization angle for harmonic component at order *h*
θ_s	Phase shift of a waveform
ω_o	Fundamental angular frequency
ω_j	Angular frequency at a DER *j*
δ_1	Constant for the regulation of steps in current dispatch
B	A MG node from the main simulation testbench
C_f	Capacitor of LC and LCL filters
$i(t)$	Time-domain current
i^{DER}	Time-domain current of a DER

i^{DER*}	Time-domain reference current of a DER
i^{Grid}	Time-domain current of the grid
i^{P*}	Time-domain reference current for active power injection
i^{o}	Time-domain output current of a DER at its PoC, or at the MG PCC
i_c	Time-domain capacitor current
i_{a_m}	Fryze's time-domain active current of a phase *m*
i_{na_m}	Fryze's time-domain non-active current of a phase *m*
i^*_{Anc}	Time-domain reference current for ancillary service provision
i^*_{ESS}	Time-domain reference current for an ESS
$i^b_{a_m}$	CPT's balanced active current of a phase *m*
$i^b_{r_m}$	CPT's balanced reactive current of a phase *m*
$i^u_{a_m}$	CPT's unbalanced active current of a phase *m*
$i^u_{r_m}$	CPT's unbalanced reactive current of a phase *m*
I_{Col}	Collective current
I_{RMS}	RMS current
I^*_h	Reference peak current to be shared by DERs at harmonic order *h*
I_h^{DERj}	Peak current of a DER *j* at harmonic order *h*
I_{nom}^{DERj}	Nominal peak current of a DER *j*
$I_{1\|\|max}^{DERj}$	Maximum active current generated by a DER *j*
$I_{1\|\|sto}^{DERj}$	Maximum active current stored by a DER *j*
I_h^{DERt}	Total peak current of DERs participating in the GCBC at harmonic order *h*
$\hat{I}_h^{DERt}$	Estimated total peak current of DERs at harmonic order *h*
I_{nom}^{DERt}	Total nominal peak current of DERs participating in the GCBC
$I_{1\|\|max}^{DERt}$	Total maximum peak current of DERs participating in the GCBC
$I_{1\|\|sto}^{DERt}$	Total stored peak current of DERs participating in the GCBC

I_h^{Grid}	Peak current of the grid at harmonic order *h*
I_h^{Grid*}	Reference peak current for the grid at harmonic order *h*
$\overline{I_{1\|\|}^{Grid}}$	Upper limit for the active current dispatch of the MG
$\overline{I_{1\perp}^{Grid}}$	Upper limit for the reactive (inductive) current dispatch of the MG
$\underline{I_{1\|\|}^{Grid}}$	Lower limit for the active current absorption of the MG
$\underline{I_{1\perp}^{Grid}}$	Lower limit for the reactive (capacitive) current dispatch of the MG
I_h^L	Peak current of loads, considering losses and non-participating DERs
$I_h^{L(b)}$	Balanced component of I_h^L after CPT decomposition
$I_h^{L(u)}$	Unbalanced component of I_h^L after CPT decomposition
I_h^{UI}	Peak current of the UI at harmonic order *h*
I_h^{UI*}	Reference peak current for the UI at harmonic order *h*
$\sqrt{\Delta I}$	Total current capability of all DERs participating in the GCBC
$\sqrt{\Delta I^{DER_j}}$	Total current capability of a DER *j*
ΔI	Quadratic total current capability of all DERs at actual step of the GCBC
ΔI_{old}	Quadratic total current capability of all DERs at previous step of the GCBC
j	*j*-th DER (*j*=1,2,3,...,*J*)
k	Actual control cycle
f_s	Sampling frequency
f_{sw}	Switching frequency
f_{GCBC}	GCBC algorithm interruption frequency
K_P	Proportional gain
K_I	Integral gain
K_f	Repetitive gain
K_{damp}	Gain of the active damping loop
L_B	Load connected to a node *B*

L_i	Inverter-side inductor of LC and LCL filters
L_g	Grid-side inductor of a LCL filter
m	Refers to phase m of an electric circuit
P^{Fryze}	Fryze's active power
P_{max}^{DERj}	Maximum active power of a DER *j*
P_{nom}^{DERj}	Nominal active power of a DER *j*
Q_{max}^{DERj}	Maximum (inductive) reactive power of a DER *j*
Q_{min}^{DERj}	Maximum (capacitive) reactive power of a DER *j*
Q_{nom}^{DERj}	Nominal reactive power of a DER *j*
r_{dDERs}	Proportion ratio among d-DERs
v^{Grid}	Time-domain voltage of the grid
v^{DERj}	Time-domain voltage of a DER *j* at its PoC
V_{RMS}^{DERj}	RMS phase voltage of a DER *j* at its PoC
V_{RMS}^{Grid}	RMS phase voltage of the grid
V_{Col}	Collective voltage
$\bar{V}$	Average of RMS voltages
$\bar{V}^{lim}$	Threshold for overvoltage detection
$\bar{V}_{lower}^{lim}$	Critical limit for undervoltage condition
$\bar{V}_{upper}^{lim}$	Critical limit for overvoltage condition
T_D	Time delay
T_s	Sampling time
T_{GCBC}	GCBC algorithm interruption time
x_h	Unitary reference signal at harmonic order *h*
Z_L	Line impedance

Chapter 1

Introduction

1.1 Background and Motivation

Decarbonization is a growing trend in the energy sector [1], and renewable energy generation plays a vital role in supporting such an energy transition [2], pushing electric power systems toward new operational and economic paradigms [3]. The immediate request to integrate renewable energy sources (RESs) into electrical grids is tied to benefits, such as the decentralization of generation, which increases the reliability in power dispatch [4]. In addition, integration of RESs provides a more diverse energy matrix that favors economic gains [5]. Nevertheless, as the proliferation of RESs increases, previously unknown technical and policy-related challenges arise [6], demanding research into new operational and regulatory strategies [7] for electric power systems.

Typically, RESs are small-scale energy generators that operate interconnected to electrical grids, by means of power electronic converters. Such an incorporation of power interfacing devices to RESs is part of the concept of distributed energy resources (DERs) [8]. In fact, DERs may also comprise energy storage systems (ESSs), and other complementary embedded technologies and functionalities, such as communication interfaces and remote control capabilities [9]. Hence, although RESs are in the spotlight of the actual energy transition [3], their potential benefits to electric systems cannot be fully exploited without the conceptualization of DERs.

In AC electrical systems, DC-AC power converters (i.e., so-called inverters) are the main electronic units of DERs in relation to the provision of controlled power conversion from RESs (e.g., photovoltaic- (PV) and wind-based generators), as well as from ESSs. A schematic of an inverter-based DER connected to an AC power system is depicted in Fig. 1.1. Converting power through inverters is possible due to their power electronics infrastructure [10], which allows the possibility to modulate voltage and current waveforms through the commutation of power switches. Concomitantly, the control algorithms embedded to such inverters are the ones responsible for dictating the operational features of DERs [11], adapting their voltages and currents according to energy generation and grid quantities. For instance, DERs can be managed to pursue local or global goals [12], leading to enhanced operation at their particular electric

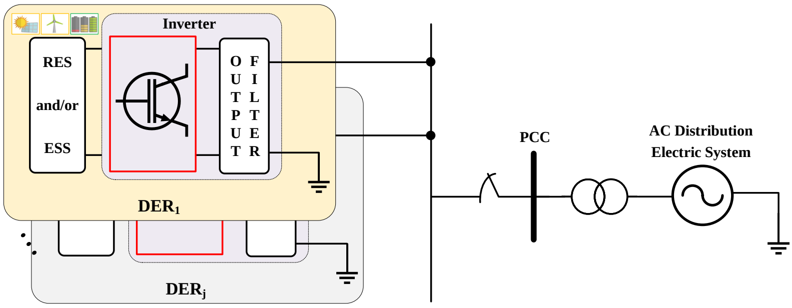

Figure 1.1: Schematic of a DER composed of a RES or ESS, and its inverter connected to an AC distribution system.

nodes, or at their entire interconnected grid, respectively.

Conventional inverters existing within DERs are commonly designed to only process active power, providing a dispatch of RESs' generated energy to the electrical grid. However, in recent years, led by the trend for *Smart Grids* (SGs) [12, 13], the concept of smart inverters has enlightened new perspectives on the purpose of such equipment [14, 15]. Beyond the provision of active power conversion, smart inverters (also called multifunctional inverters) offer the possibility to employ their rated capabilities in services related to power conditioning and grid support [16]. Thus, flexible implementation of power quality interventions, and more sophisticated power distribution planning strategies have become possible [17].

To implement such a perspective, the control flexibility of inverter-based DERs can be exploited to offer ancillary functionalities, such as voltage support to the grid [18], compensation of power oscillations and unbalanced currents [14], mitigation of reactive and harmonic components [19], and many others [15]. Moreover, since information and communication technologies (ICTs) are intrinsic to SGs, communication features are becoming compulsory for inverters [8]. This consequently allows them to support remote control and interoperability, while broadening their applications to scenarios of cooperative and coordinated operations [14, 20].

As more and more multifunctional abilities are being incorporated into electrical grids, especially from the perspective of low-voltage (LV) power systems, the locally-oriented operation of inverters is doomed to become obsolete. This occurs because operation of DERs under individualized perspectives (i.e., purely local) does not take into account the status of other equipment or the overall needs of the grid. Moreover, non-coordinated DER actions may interfere with the proper functioning of their neighboring inverters [21], as well as impairing grid stability [22]. To corroborate such undesired effects of interacting DERs, one can observe issues like the multi-timescale coupling among their control loops [23], and the generation of circulating currents caused by the lack of synergy during their parallel operation [21].

On the other hand, as reinforced in [23], if proper coordination among multifunctional inverters is formulated, more reliability and robustness can be achieved from both local and global operational perspectives. Thus, the coordinated control of DERs not only offers enhanced use of inverters' power capabilities, but also decreases the undesired side-effects of their local functioning. Furthermore, proper coordination of ancillary services devised by smart inverters dispersed over AC grids can even optimize the profitability of prosumers (i.e., DERs' owners that also comprise local consumption) [24]. Moreover, this also supports the offering of energy management features to benefit entities at power system levels [25].

The importance of coordinating inverters is further evidenced in the so-called weak grids, which are power systems comprising low short-circuit ratio and small inertia constant [26]. In such a scenario, the significant presence of DERs potentially affects the grid capability to maintain steady and compliant voltage profiles. Consequently, this results in a chain effect that may interfere with the adequate operation of loads and grid-tied converters [26], as well as potentially lead to the propagation of non-idealities (e.g., harmonic distortions) [27] to adjacent distribution grids [28].

This condition is particularly frequent, and critical, in weak microgrids (MGs), which are defined by [29] as power systems that: *i)* present clearly established electrical boundaries; *ii)* comprise a considerable amount of loads and interconnected DERs; *iii)* have the capability to act as a single controllable entity, with respect to its point-of-connection (PCC) with an upstream grid (see Fig. 1.1); and that *iv)* are able to operate both interconnected and islanded (i.e., under autonomous mode [30]). Given all the particularities of MGs, their design, operation and management have been extensively explored in the literature [31, 32, 33, 34], often converging on the conclusion that proper coordination of DERs is imperative.

Since ICT is being widely incorporated into the infrastructure of electric grids, along with the fact that MGs can be interpreted as individual entities, smartness can also be extended to how such systems behave and operate. Smart MGs, for instance, are systems that are intelligently self-sufficient (i.e., internally exploiting their resources to be fully independent) [35]. Moreover, they are capable of dynamically interacting with external agents to optimize internal and external financial and operational objectives [36].

As a result, if a smart MG is flexibly modeled and managed to act according to market and technical requirements, it can accordingly take part in controlled energy transactions [37]. Hence, smart MGs possess the means to interact with external agents (e.g., the distribution system operator (DSO), aggregators or other MGs) to trade market-regulated energy services. Among the examples of such services provided by LV MGs, one can find controllable power dispatchability [25], and power quality support to achieve more robust operation of distribution grids [38].

The summary presented in Fig. 1.2 represents the scalable complexity of how the context of RESs and SGs is impacting on how equipment (such as inverters) and power systems (such as MGs) are evolving and interacting with other entities. It can be noted that, although each of the previous discussions may be seen as an independent topic, all concepts are fundamental pieces of the overall infrastructure of real SGs. Although the practical model of SGs is complex, extending from consolidated concepts like automation and digitalization, up to emerging ideas such as the energy internet [39], it can be first realized by intelligently operating equipment that supports basic principles, such as interoperability.

The background of this PhD thesis is also immersed within the multidisciplinary context found in Fig. 1.2. By assimilating different SG concepts, the scope of this thesis encompasses the idea of how multiple technological principles (e.g., smart inverters, coordinated control, energy services) can be integrated to obtain the flexible operation of MGs. Beyond basic management features, the consideration of non-ideal operational conditions is also of interest to this thesis, not to mention the importance of accounting for market-oriented applicability. Thus, in summary, the grounds of this thesis take into consideration the employment of smart inverters as potential tools to improve the management of MGs, under diverse operational conditions, also investigating possibilities to broaden the provision of ancillary energy services focusing on the LV perspective.

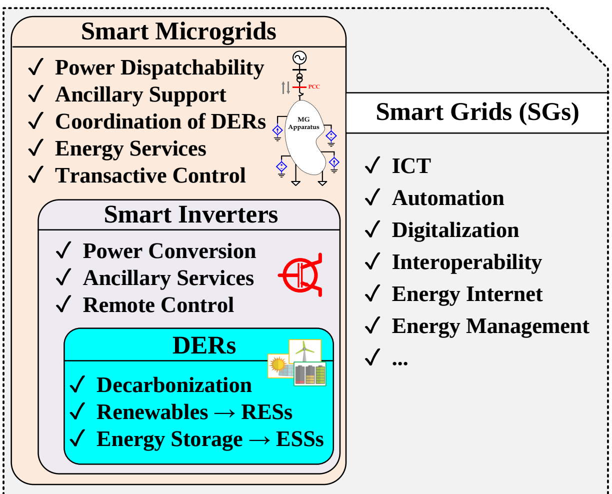

Figure 1.2: Background context of DERs, smart inverters and MGs within the scenario of SGs.

1.2 Main Goals and Contributions

1.2.1 Main Goals of the PhD Thesis

This PhD thesis is grounded in the perspective of a smart AC MG comprising a significant amount of DERs of different natures, considering that their inverters have the capability to operate as multifunctional devices offering ancillary services. The targeted scenario holds homogeneous features, indicating that DERs, loads and line impedances are fairly evenly distributed throughout the MG. In addition, since a MG acts most of the time under the interconnected mode [5], this thesis also focuses on the features of its operation as a single-controllable entity, assessing how it can contribute to the support of an upstream distribution network.

Based on the above-mentioned conceptualization, the major objective of this thesis is to develop a coordinated control strategy to allow transactive and multi-purpose steering of DERs dispersed over an AC MG, focusing on the LV perspective. The transactive control aspect of such a strategy [40] is intended to support the possibility for the MG to trade energy services with external agents. Consequently, the flexibility to achieve market-oriented management over active power dispatchability, in addition to the extended provision of ancillary services, is offered. Furthermore, the proposed multi-purpose feature relates to the fact that, beyond providing controllable power extraction from DERs, distributed compensation of unwanted current components, as well as voltage regulation, can be pursued.

Another goal of this thesis is to ensure that the proposed coordination of inverters is valid under non-ideal operational scenarios, such as non-sinusoidal voltages, abnormal voltage scenarios, as well as under ICT-related issues. Such goals imply that, by providing flexible steering of DERs in a MG, both local and global objectives related to power exploitation, power quality, grid support, and market-oriented actions can be obtained.

The main goals of this thesis are explicitly highlighted as follows. They specify the idea of developing a coordinated control strategy that grants:

1. *Model-free formulation and flexible implementation*

   In order to deploy the strategy, features that facilitate its real implementation are desirable, for the sake of practicality and commercial attractiveness. Hence, a goal is set by developing a strategy that is: *i)* topology independent, *ii)* model-free, and *iii)* plug-and-play.

   The topology independence of the strategy strives to make it applicable to AC MGs, regardless if they are based on single- [41], three-phase, or other poly-phase circuits [42]. The model-free aspect implies that knowledge of MG parameters (e.g., line impedance characteristics, location of DERs or loads, features of transformers, etc.) are not essential for the adequate and proportional steering of DERs [43]. In addition, the plug-and-play feature relates to the self-adjusting capability of the control strategy to dynamically rearrange the coordination of inverters during changes in the MG;

2. *Adjustable active power conversion*

   Since the main purpose of DERs is to inject active power into grids, it is important to achieve controllability over such functionality. Thus, energy exploitation can efficiently occur without affecting grid performance. Additionally, as power generation profiles may be intermittent or limited, variability in the local operation of DERs should be supported. Lastly, DERs of a dispatchable (e.g., endowing ESSs) and non-dispatchable (e.g., PV- or wind-based) nature may exist (i.e., herein denoted as d- and nd-DERs), so that the strategy must cope with their synergistic operation;

3. *Distributed compensation of unwanted currents*

   In AC MGs, reactive, harmonic and unbalanced current components are tied to the lowering of energy efficiency and deterioration of power quality [27]. Hence, the control strategy intends to exploit dispersed inverters to also provide distributed compensation of reactive currents, as well as selective mitigation of harmonics. The compensation of unbalanced currents is also considered for particular implementations;

4. *Operation upon adverse scenarios*

   In general, LV MGs are known to be weak systems, in which voltage waveforms cannot always be ideal (i.e., sinusoidal with constant magnitude). Consequently, the goal of ensuring that the proposed coordinated control strategy presents robust operation under non-ideal scenarios is accounted for. In particular, this thesis presents an assessment of the control approach upon scenarios of distorted voltages, as well as considering voltage ride-through challenges. Another research target is to demonstrate the features of the strategy under the occurrence of ICT-related issues, such as faulty communication links and delays in data transmission;

5. *MG dispatchability and support to transactive control*

   The key factor in the MG participation in energy transactions [37] is the ability to achieve full power dispatchability. This thesis has the objective of demonstrating that, by adequately coordinating DERs, the energy flow at the MG PCC can be regulated to achieve decoupled active, reactive and harmonic controllability. Consequently, access to market-oriented transactions of active power flow is individually possible. In addition, the reactive and harmonic power flow control at the PCC can support the planning of power dispatch for the upstream grid and provide high power factor operation, respectively, being interpreted as marketable energy services. Finally, full controllability over active and non-active currents at the PCC also offers the possibility for the MG to operate under self-consumption mode [44] (i.e., neither depending on the upstream grid, nor significantly affecting its operation).

6. *Voltage regulation capability*

   While exploiting DERs in distribution systems, it is important to ensure that voltage profiles are maintained within acceptable ranges [8], foremost in the internal nodes of the MG. With this in mind, this thesis also strives to develop a coordinated control strategy that sustains the regulation of voltage profiles, if overvoltage conditions occur internally to the MG. The availability of several DERs to contribute to voltage regulation is also taken into account.

7. *Experimental validations*

   Since the development of the coordinated control strategy reaches the power electronics layer, it is important to validate the applicability of the proposed functionalities to real-life implementations. As a result, beyond demonstrating computational simulations, laboratory scale prototypes have been set up to experimentally assess the performance of the coordination approach.

1.2.2 Contributions of the PhD Thesis

This thesis explicitly presents the following scientific and nonscientific contributions, which are also evidenced by the scientific publications presented in Section 1.3:

Scientific Contributions

1. The development of a centralized strategy that provides multi-purpose coordinated control of inverters in transactive MGs. The coordination approach, so-called Generalized Current-Based Control (GCBC), is formulated based on the analysis of electrical currents flowing within the MG, also considering power exchange interactions with the upstream distribution grid at the PCC. The GCBC encompasses all the features previously explained in Section 1.2.1 for goal 1, while also endowing control capabilities to achieve goals 2 to 5.

2. A systematic assessment of the features of the proposed coordination approach is realized, by means of computational simulations and extensive experimental work, being carried out on multiple simulation testbenches and laboratory-scale MG prototypes. Beyond evaluating non-ideal scenarios of operation, comparative studies with another well-known coordination strategy (i.e., droop control

[31]) are conducted to highlight the particularities and contributions of the proposed method;

3. An innovative approach is proposed to devise a resistive shaping for the PCC of an interconnected MG, considering that the upstream distribution grid operates while suffering from distorted voltages. The method provides high power factor operation and, upon the existence of resonant components, it supports harmonic resonance damping, which minimizes deterioration of voltage quality. In addition, the control approach holds improved performance when compared to strategies that aim to fully mitigate harmonic currents;

4. A method to steer DERs to achieve distributed and decoupled compensation of unbalanced currents in MGs, without requiring the implementation of virtual impedance control loops [31], nor the extraction of sequence components. Such an approach incorporates the Conservative Power Theory (CPT) [45] for generating reference currents for the compensation purposes;

5. Taking advantage of the MG power dispatchability, an automatic voltage regulation scheme is formulated. It is demonstrated that the energy exploitation of non-dispatchable inverters can be enhanced without optimization algorithms, while ensuring that overvoltage conditions are mitigated internally to the MG. This occurs by the synergistic active and reactive power control of d- and nd-DERs. Additionally, the proposed strategy allows the possibility to integrate DERs into voltage regulation regardless of their location in the MG;

6. An extended outlook on the power dispatchability of transactive MGs is presented, demonstrating that multiple ancillary services can be provided. Moreover, a transactive control framework for MGs is designed, relying on the steering of DERs to offer the flexible provision of energy services in the power system level, thus supporting accessibility to electricity markets.

Nonscientific Contributions

1. Two main contributions relate to UNESP/Sorocaba-Brazil. The first one concerns the implementation of two experimental MG prototypes being: *i)* one composed of three-phase inverters; and *ii)* one devised by the realization of technical improvements in a previously existent single-phase platform. Beyond the fact that both testbenches can be used in future research, they lead to the second contribution, which is the incorporation of these experimental infrastructures into the activities executed for the thematic project "*Interdisciplinary Research Activities in Electric Smart Grids*" [46], which is funded by *FAPESP*;

2. Two last contributions relate to NTNU/Trondheim-Norway. This PhD thesis is also a direct outcome of the "*Norwegian-Brazilian Collaboration on*

Power Theories and Cooperative Control for Renewable Energy Integration (NB_POCCREI)" project [47], which was funded by the the *Research Council of Norway*. Additionally, the interactions resulting from this thesis led to a Cotutelle agreement for a double degree PhD, taking part in strengthening the scientific cooperation between NTNU and UNESP.

1.3 List of Publications

During the three-year period of this PhD project, the main scientific findings have been published in the following journal and conference articles. Such publications present results obtained as a direct outcome of this PhD research, also comprising additional contributions in correlated topics.

Journal Papers:

J.1) **A. M. S. Alonso**, D. I. Brandao, E. Tedeschi, and F. P. Marafao, "Resistive Shaping of Interconnected Low-Voltage Microgrids Operating Under Distorted Voltages," *IEEE Transactions on Industrial Electronics*, 2021. Accepted

J.2) **A. M. S. Alonso**, L. O. Arenas, D. I. Brandao, E. Tedeschi, and F. P. Marafao, "Automatic Overvoltage Control of Distributed Energy Resources Supporting Enhanced Energy Exploitation in Interconnected Microgrids," *IEEE Transactions on Sustainable Energy*, 2021. Under Review

J.3) **A. M. S. Alonso**, J. H. Oliveira, D. I. Brandao, J. P. Bonaldo, H. K. M. Paredes, and F. P. Marafao, "A Multifunctional Grid-Tied Inverter for Two-Phase Three-Wire Networks Based on the Conservative Power Theory," *IEEE Transactions on Power Delivery*, 2021. Under Review

J.4) **A. M. S. Alonso**, D. I. Brandao, E. Tedeschi, and F. P. Marafao, "Distributed Selective Harmonic Mitigation and Decoupled Unbalance Compensation by Coordinated Inverters in Three-Phase Four-Wire Low-Voltage Networks," *Electric Power Systems Research*, vol. 186, pp. 1–14, 2020.

J.5) **A. M. S. Alonso**, D. I. Brandao, T. Caldognetto, F. P. Marafao, and P. Mattavelli, "A Selective Harmonic Compensation and Power Control Approach Exploiting Distributed Electronic Converters in Microgrids," *International Journal of Electrical Power & Energy Systems*, vol. 115, pp. 1–15, 2020.

J.6) **A. M. S. Alonso**, B. R. Pereira Jr., D. I. Brandao, and F. P. Marafao, "Optimized Exploitation of Ancillary Services: Compensation of Reactive, Unbalance and Harmonic Currents Based on Particle Swarm Optimization," *IEEE Latin America Transactions*, vol. 19, no. 2, pp. 314-325, 2021.

J.7) L. S. De Araujo, **A. M. S. Alonso**, and D. I. Brandao, "Decentralized Control

of Voltage- and Current-Controlled Converters Based on AC Bus Signaling for Autonomous Microgrids," *IEEE Access*, vol. 8, pp. 202075–202089, 2020.

J.8) J. P. Bonaldo, J. A. O. Filho, **A. M. S. Alonso**, F. P. Marafao, H. K. M. Paredes, "Modeling and Control of a Single-Phase Grid-Connected Inverter with *LCL* Filter," *IEEE Latin America Transactions*, vol. 19, no. 2, pp. 205-259, 2021.

J.9) D. I. Brandao, W. M. Ferreira, **A. M. S. Alonso**, E. Tedeschi, and F. P. Marafao, "Optimal Multiobjective Control of Low-Voltage AC Microgrids: Power Flow Regulation and Compensation of Reactive Power and Unbalance," *IEEE Transactions on Smart Grid*, vol. 11, no. 2, pp. 1239–1252, 2020.

J.10) D. I. Brandao, L. S. Araujo, **A. M. S. Alonso**, G. L. dos Reis, E. V. Liberado, and F. P. Marafao, "Coordinated Control of Distributed Three- and Single-Phase Inverters Connected to Three-Phase Three-Wire Microgrids," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 4, pp. 3861–3877, 2020.

Conference Papers:

C.1) **A. M. S. Alonso**, L. O. Arenas, R. T. Hock Jr., H. Guillardi Jr., H. K. M. Paredes, F. A. S. Goncalves, and F. P. Marafao, "Experimental Implementation of a Single-Phase Microgrid: A Flexible Resource for Research and Educational Activities," in *2021 IEEE 16th Brazilian Power Electronics Conference (COBEP)*, 2021. Accepted

C.2) **A. M. S. Alonso**, F. Göthner, D. I. Brandao, F. P. Marafao, and E. Tedeschi, "Power- and Current-Based Control of Distributed Inverters in Low-Voltage Microgrids: Considerations in Relation to Classic Droop Control," in *2020 15th International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2020, pp. 1–10.

C.3) **A. M. S. Alonso**, L. C. Afonso, D. I. Brandao, E. Tedeschi, and F. P. Marafao, "Considerations on Communication Infrastructures for Cooperative Operation of Smart Inverters," in *2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC)*, 2019, pp. 1–6.

C.4) **A. M. S. Alonso**, H. K. M. Paredes, J. A. O. Filho, J. P. Bonaldo, D. I. Brandao, and F. P. Marafao, "Selective Power Conditioning in Two-phase Three-Wire Systems Based on the Conservative Power Theory," in *2019 IEEE Industry Applications Society Annual Meeting*, 2019, pp. 1–6.

C.5) **A. M. S. Alonso**, D. I. Brandao, F. P. Marafao, and E. Tedeschi, "Coordinated Control of Parallel Power Conditioners Synthesizing Resistive Loads in Single-Phase AC Microgrids," in *2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe)*, 2019, pp. 1–9.

C.6) **A. M. S. Alonso**, D. I. Brandao, E. Tedeschi, and F. P. Marafao, “Distributed Harmonic Compensation in Single-Phase Low-Voltage Microgrids,” in *XXII Brazilian Conference on Automation (CBA)*, 2018, pp. 1–8.

The above-mentioned publications support multiple chapters of this thesis, and they can be mapped according to Table 1.1. Moreover, it is highlighted that the following three additional papers are currently being written: *i)* one journal paper, being an extension of "C.2", which has been invited for possible publication in *IEEE Transactions on Industry Applications*; *ii)* one journal paper comprising the results from Section 5.5; and *iii)* one conference paper composed of discussions presented in Chapter 2.

Table 1.1: Mapping of publications to chapters.

Chapter	2	3	4	5	6
Journal	-	*J.3, J.4, J.5, J.8*	*J.4, J.5, J.7, J.10*	*J.5*	*J.1, J.2, J.4, J.6 J.8, J.9, J.10*
Conference	-	*C.2, C.3, C.6*	*C.1, C.2, C.6*	*C.6*	*C.4, C.5*

1.4 Structure of the Thesis

Besides its introductory part, this thesis is structured into six additional chapters, aiming at plainly conveying the ideas and contributions comprised within the proceeding discussions.

Firstly, in Chapter 2, the transactive aspect of MGs is presented. The concept of Transactive Energy Systems (TESs) is introduced, and the MG power dispatchability is discussed as a means to offer energy services, constituting a market-oriented outlook.

Chapter 3 explains the MG and DER topologies considered within this thesis, and it presents the basic formulation of the proposed multi-purpose coordination of DERs (i.e., the GCBC approach). The hierarchical control infrastructure of the strategy, as well as its flexibility to control multiple current components, is thoroughly explained.

The multiple functionalities and transactive features of the GCBC strategy are demonstrated in Chapter 4, in which extensive simulations and experimental results are discussed. Moreover, additional operational considerations, such as the MG transition modes and a comparison with the droop control approach, are discussed.

Adverse operational scenarios, such as under distorted voltages, upon ICT-related issues, and consideration of the matter of power coupling among DERs, are assessed in Chapter 5. The goal of the discussions in this chapter is to show that the GCBC approach is flexible and resilient for implementation in weak LV MGs.

Advanced control functionalities related to the resistive shaping of MGs, distributed compensation of unbalanced currents, and voltage regulation capabilities are provided in Chapter 6. Moreover, a brief discussion about the integration of optimization approaches to the coordination strategy is also given.

Lastly, Chapter 7 presents the final conclusions of the PhD thesis, and offers proposals for the development of future works.

Chapter 7

Conclusions

7.1 General Conclusions

In this thesis, a multi-purpose coordinated control strategy has been presented to flexibly steer inverter-based DERs, focusing on the scenario of LV MGs participating in transactive energy markets. Such a control approach, namely GCBC, relies on a hierarchical architecture, and it uses a centralized unit (i.e. the MGCC) to adjust the operation of inverters according to the desired MG operational goals.

The GCBC strategy is formulated based on the analysis of peak currents flowing within the MG, and it presents a model-free feature, which provides a means to coordinate DERs without previous knowledge of the MG's physical parameters (e.g, line impedances values). A synergistic interaction between both dispatchable and non-dispatchable inverters is supported by the GCBC, guaranteeing that the strategy can cope with realistic scenarios of LV MGs. In addition, the coordinated steering of DERs allows the MG to achieve internal objectives, also offering operational functionalities that support the energy planning of an upstream distribution grid.

The multifaceted perspective of transactive MGs was discussed in Chapter 2, pointing out their multiple possibilities of interactions in energy markets, under both financial and technical aspects. Besides this, a transactive control framework was presented to clarify the participation of MGs as market players, as well as highlighting their technical role in the scenario of cellular electric systems. Moreover, an extended outlook on ancillary functionalities was discussed, situating MGs as key players in the provision of grid-supporting energy services.

The infrastructure of the considered LV MG topology was presented in Chapter 3, explaining the scope of application of this thesis. The elementary local control infrastructures of nd- and d-DERs were briefly presented, showing that they can offer active power conversion from RESs or ESSs, and that smart inverters can also support the provision of ancillary services. The three-layer hierarchical architecture of the GCBC strategy was explained in detail, highlighting how the approach steers DERs, as well as explaining how the MG interacts with external agents. Additionally, the basic formulation of the GCBC strategy was also discussed, demonstrating that the analysis of peak currents can offer current sharing capabilities for DERs, as well as showing that the MG can be controlled as a single dispatchable entity.

Multiple purposes of operation for the MG were exemplified in Chapter 4, by means of simulation and experimental results. It has been demonstrated that the GCBC strategy allows us to control inverters to pursue active and reactive current sharing, supplying loads and alleviating the upstream grid from this burden. Moreover, the purpose of achieving distributed and selective compensation of harmonic currents has been demonstrated, by itself and while integrated into the control of fundamental currents. Thus, beyond controlling inverters to compensate non-active currents, the GCBC offers to the MG the possibility of operating under full self-consumption mode. Yet, as intermittency is inherent to distributed generation systems, the strategy can cope with variable generation profiles.

The MG power dispatchability has also been explored in Chapter 4, giving support to the major transactive aspect of the MG, which is related to energy trading capability. Both absorption and dispatch of active currents can be controlled at the MG PCC, as long as DERs present sufficient energy generation and nominal capabilities to support the intended goal. Yet, such a feature is conditional on the fact that MG contractual constraints should always be obeyed, as well as compliance with grid codes. Furthermore, reactive power dispatch can be offered either independently or concomitantly to active power control, giving more flexibility for the MG to sell energy services in transactive markets. Chapter 4 has also demonstrated that the MG functionalities offered by the GCBC strategy are not affected by the features of line impedances, guaranteeing that proportional sharing of currents occurs among DERs, in contrast to strategies such as the conventional droop control.

Since LV MGs are usually weak systems, they are susceptible to operating under non-ideal scenarios. Hence, Chapter 5 highlighted the particularities of the GCBC approach when inverters operate under limited power ratings. Additionally, it has been demonstrated that the strategy endures operation when voltages are highly distorted, as well as that it presents voltage ride-through capabilities. Another interesting feature related to the adoption of the GCBC strategy, particularly for homogeneous MGs, is that it provides voltage quality improvement as an indirect outcome of the proportional sharing of non-active currents. Finally, considerations on stability, communication matters and power coupling are concluded in Chapter 5, indicating that the GCBC presents operational concerns that, although not critical from a stability standpoint, need to be taken into account prior to deploying the strategy.

Advanced control functionalities have been presented in Chapter 6, providing enhanced operational features for LV MGs. It has been demonstrated that, based on a few adaptions of the GCBC strategy, the MG can be shaped to operate as a variable resistor when voltage distortions exist, allowing high power factor operation at the PCC, and supporting the damping of harmonic resonances. Voltage regulation has also been devised in Chapter 6, by means of an automatic approach that provides coordinated Volt/Watt and Volt/VAR actions, allowing us to minimize the curtailment of active power from nd-DERs. Finally, an approach based on the CPT was incorporated into the GCBC, providing a means to achieve distributed compensation of unbalanced active and reactive currents.

In summary, the overall conclusion of this thesis is that the GCBC strategy allows the possibility of offering multiple functionalities for LV MGs. Both internal and external operational purposes of MGs can be considered while exploiting DERs, and the integration of technical and market-related objectives can be taken into account. Thus, the control approach can be seen as an innovative alternative to coordinate DERs in MGs, contributing to the movement of the electric sector towards the implementation of smarter grids.

7.2 Future Works

The following scientific aspects have been identified as prospective topics for future works, aiming at expanding and giving continuity to the contributions found within this PhD thesis.

a) **Optimal regulation of the MG operation:** Even though multiple operational purposes can be offered by the GCBC strategy, MGs must dynamically adjust their goals according to real-life oriented market indexes and energy generation forecasts [220]. Thus, optimal approaches [66, 217] can be devised to efficiently exploit the capabilities of DERs, steering them to better attend to the needs of the MG. Multi-objective actions can be modeled for the MG, allowing the possibility to optimize its internal usage of energy, as well as improving economic profitability for prosumers and the MG manager;

b) **MG power dispatchability supporting cellular electric systems:** The coordinated control strategy proposed in this thesis allows us to flexibly adjust the MG power dispatchability, also shaping the PCC to emulate different behaviors for the upstream grid. Consequently, the external interactions of the MG can be included in the energy planning horizon of cellular electric systems (i.e., power systems comprising multiple interconnected and supervised MGs, such as in cluster topologies [52, 55]). Such operationality can to incorporate controllable provision of distributed energy generation in an utility scale. Moreover, ancillary services can be offered under the power system perspective, supporting voltage and frequency regulation, congestion management, as well as power quality improvement;

c) **Coordination of single- and three-phase DERs arbitrarily connected to three-phase MGs:** Although in this thesis simulation and experimental results only considered either single- or three-phase inverters, LV MGs commonly present DERs based on both topologies. Similarly to [68] and [71], the GCBC strategy can be extended to accommodate both single- and three-phase inverters in three-phase MGs to support the sharing of fundamental currents. Additionally, distributed compensation of harmonic currents using both inverter topologies, which has been rarely studied in the literature, can be investigated based on the GCBC strategy;

d) **Coordination of DERs under asymmetrical voltages:** Asymmetries in voltages often occur in weak grids, and the coordination of DERs should take that issue into account. Further studies can conducted using the GCBC strategy to understand how DERs can be steered to mitigate voltage unbalances, as well as to shape the MG PCC to achieved different operational behaviors, such as the one of balanced conductances or susceptances [148];

e) **Redesign the GCBC strategy following a distributed control architecture:** Since the GCBC strategy relies on a centralized architecture, the existence of the MGCC is unavoidable. Nevertheless, if the calculation required to attain control references can be performed under a distributed architecture [226], multi-purpose control can be supported without a central agent. Thus, improved reliability can be achieved, as communication issues become less critical;

f) **Fair voltage regulation:** The automatic voltage regulation scheme proposed in Section 6.3 coordinates d-DERs only proportionally to their nominal ratings and generation capabilities. Consequently, the natural discrepancy occurring among their voltage magnitudes, which is caused by voltage drops through line impedances, is not taken into account. Hence, if the concept of fair overvoltage [205] control is incorporated to the GCBC strategy, all d-DERs (i.e., even those placed close to the DST) can contribute to voltage regulation proportionally to their voltage magnitudes. This feature would allow us to obtain a more equalized voltage profile for all nodes of the MG.

Bibliography

[1] G. Luderer, M. Pehl, and A. Arvesen, "Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies," *Nature Communications*, vol. 10, pp. 1–13, 2019.

[2] IRENA, *Global Renewables Outlook: Energy Transformation 2050*. International Renewable Energy Agency, Abu Dhabi, 2020.

[3] N. Vandycke, "World Economic Forum: Can electricity decarbonize the energy sector?" https://www.weforum.org/agenda/2020/04/can-electricity-decarbonize-the-energy-sector/, Accessed: 10.09.2020.

[4] A. J. Veldhuis, M. Leach, and A. Yang, "The impact of increased decentralised generation on the reliability of an existing electricity network," *Applied Energy*, vol. 215, pp. 479–502, 2018.

[5] S. Wang, Y. Huang, I. Vorushylo, H. Chen, D. McLarnon, P. MacArtain, and N. Hewitt, "Economic assessment of high renewable energy penetration scenario in 2030 on the interconnected irish power system," *Energy Policy*, vol. 145, p. 111774, 2020.

[6] K. Bell and S. Gill, "Delivering a highly distributed electricity system: Technical, regulatory and policy challenges," *Energy Policy*, vol. 113, pp. 765–777, 2018.

[7] G. P. Holdmann, R. W. Wies, and J. B. Vandermeer, "Renewable energy integration in alaska's remote islanded microgrids: Economic drivers, technical strategies, technological niche development, and policy implications," *Proceedings of the IEEE*, vol. 107, no. 9, pp. 1820–1837, 2019.

[8] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Asiated Electric Power Systems Interfaces*, IEEE Std. 1547-2018 (Revision of IEEE Std 1547-2003), 2018.

[9] P. Jonke, B. Sumanta, F. Andrén, J. Stöckl, and T. Strasser, "Rapid prototyping of distributed energy resources integrating ICT and power electronics design," in *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, 2014, pp. 3591–3597.

[10] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics. Converters, Applications and Design*, 3rd ed. John Wiley and Sons, Inc, 2003.

[11] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of power converters in ac microgrids," *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4734–4749, 2012.

[12] A. Gopstein et al, "Draft: NIST framework and roadmap for smart grid interoperability standards, release 4.0," National Institute of Standards and Technology (NIST), Tech. Rep., July 2020.

[13] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid — the new and improved power grid: A survey," *IEEE Communications Surveys Tutorials*, vol. 14, no. 4, pp. 944–980, 2012.

[14] B. Mirafzal and A. Adib, "On grid-interactive smart inverters: Features and advancements," *IEEE Access*, vol. 8, pp. 160 526–160 536, 2020.

[15] B. Arbab-Zavar, E. J. Palacios-Garcia, J. C. Vasquez, and J. M. Guerrero, "Smart inverters for microgrid applications: A review," *Energies*, vol. 12, pp. 1–22, 2019.

[16] Y. Yang, F. Blaabjerg, H. Wang, and M. G. Simoes, "Power control flexibilities for grid-connected multi-functional photovoltaic inverters," *IET Renewable Power Generation*, vol. 10, no. 4, pp. 504–513, 2016.

[17] B. Enayati et al, "Impact of IEEE 1547 standard on smart inverters," The Institute of Electrical and Electronics Engineers (IEEE), Tech. Rep. PES-TR67, May 2018.

[18] J. C. Vasquez, R. A. Mastromauro, J. M. Guerrero, and M. Liserre, "Voltage support provided by a droop-controlled multifunctional inverter," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 11, pp. 4510–4519, 2009.

[19] F. P. Marafao, D. I. Brandao, A. Costabeber, and H. K. M. Paredes, "Multi-task control strategy for grid-tied inverters based on conservative power theory," *IET Renewable Power Generation*, vol. 9, no. 2, pp. 154–165, 2015.

[20] Y. Xue and J. M. Guerrero, "Smart inverters for utility and industry applications," in *Proceedings of PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2015, pp. 1–8.

[21] Y. Qi, P. Lin, Y. Wang, and Y. Tang, "Two-dimensional impedance-shaping control with enhanced harmonic power sharing for inverter-based microgrids," *IEEE Transactions on Power Electronics*, vol. 34, no. 11, pp. 11 407–11 418, 2019.

[22] S. Liao, M. Huang, X. Zha, and J. M. Guerrero, "Emulation of multi-inverter integrated weak grid via interaction-preserved aggregation," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2020.

[23] Q. Peng, Q. Jiang, Y. Yang, T. Liu, H. Wang, and F. Blaabjerg, "On the stability of power electronics-dominated systems: Challenges and potential solutions," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7657–7670, 2019.

[24] F. Chen, M. Chen, Q. Li, K. Meng, Y. Zheng, J. M. Guerrero, and D. Abbott, "Cost-based droop schemes for economic dispatch in islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 63–74, 2017.

[25] J. R. S. Junior, D. I. Brandao, N. T. D. Fernandes, W. Utuerbey, and B. Cardoso, "Multifunctional dispatchable microgrids," *Applied Energy*, vol. 282, no. Part A, p. 116165, 2021.

[26] A. Adib and B. Mirafzal, "Virtual inductance for stable operation of grid-interactive voltage source inverters," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6002–6011, 2019.

[27] A. Micallef, "Review of the current challenges and methods to mitigate power quality issues in single-phase microgrids," *IET Generation, Transmission Distribution*, vol. 13, no. 11, pp. 2044–2054, 2019.

[28] J. He, Y. W. Li, R. Wang, and C. Zhang, "Analysis and mitigation of resonance propagation in grid-connected and islanding microgrids," *IEEE Transactions on Energy Conversion*, vol. 30, no. 1, pp. 70–81, 2015.

[29] *IEEE Standard for the Specification of Microgrid Controllers*, IEEE Std. 2030.7-2017, 2018.

[30] L. S. De Araujo, A. M. S. Alonso, and D. I. Brandao, "Decentralized control of voltage- and current-controlled converters based on ac bus signaling for autonomous microgrids," *IEEE Access*, vol. 8, pp. 202 075–202 089, 2020.

[31] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical control of droop-controlled ac and dc microgrids—a general approach toward standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, 2011.

[32] D. E. Olivares, A. Mehrizi-Sani, A. H. Etemadi, C. A. Cañizares, R. Iravani, M. Kazerani, A. H. Hajimiragha, O. Gomis-Bellmunt, M. Saeedifard, R. Palma-Behnke, G. A. Jiménez-Estévez, and N. D. Hatziargyriou, "Trends in microgrid control," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1905–1919, 2014.

[33] R. H. Lasseter, "Smart distribution: Coupled microgrids," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1074–1082, 2011.

[34] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, "Networked microgrids for enhancing the power system resilience," *Proceedings of the IEEE*, vol. 105, no. 7, pp. 1289–1310, 2017.

[35] A. Hirsch, Y. Parag, and J. M. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 402–411, 2018.

[36] M. Carpintero-Rentería, D. Santos-Martín, and J. M. Guerrero, "Microgrids literature review through a layers structure," *Energies*, vol. 12, pp. 1–22, 2019.

[37] M. F. Zia, M. Benbouzid, E. Elbouchikhi, S. M. Muyeen, K. Techato, and J. M. Guerrero, "Microgrid transactive energy: Review, architectures, distributed ledger technologies, and market analysis," *IEEE Access*, vol. 8, pp. 19 410–19 432, 2020.

[38] A. Majzoobi and A. Khodaei, "Application of microgrids in providing ancillary services to the utility grid," *Energy*, vol. 123, pp. 555–563, 2017.

[39] Y. Wu, Y. Wu, J. M. Guerrero, and J. C. Vasquez, "Digitalization and decentralization driving transactive energy internet: Key technologies and infrastructures," *International Journal of Electrical Power & Energy Systems*, vol. 126, no. Part A, p. 106593, 2021.

[40] D. Holmberg et al, "NIST transactive energy modeling and simulation challenge phase ii final report," National Institute of Standards and Technology (NIST), Tech. Rep. 1900-603, May 2019.

[41] A. Micallef, M. Apap, C. Spiteri-Staines, and J. M. Guerrero, "Single-phase microgrid with seamless transition capabilities between modes of operation," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2736–2745, 2015.

[42] A. M. S. Alonso, H. K. M. Paredes, J. A. O. Filho, J. P. Bonaldo, D. I. Brandão, and F. P. Marafão, "Selective power conditioning in two-phase three-wire systems based on the conservative power theory," in *2019 IEEE Industry Applications iety Annual Meeting*, 2019, pp. 1–6.

[43] D. I. Brandao, R. Patric dos Santos, W. Silva, T. R. De Oliveira, and P. F. Donoso-Garcia, "Model-free energy management system for hybrid ac/dc microgrids," *IEEE Transactions on Industrial Electronics*, pp. 1–1, 2020.

[44] SMA, "The self-consumption bonus: Information and details regarding the self-consumption of solar energy," https://www.sma.de/en/partners/knowledgebase/the-self-consumption-bonus.html, Accessed: 2020-12-29.

[45] P. Tenti, H. K. M. Paredes, and P. Mattavelli, "Conservative power theory, a framework to approach control and accountability issues in smart microgrids," *IEEE Transactions on Power Electronics*, vol. 26, no. 3, pp. 664–673, 2011.

[46] FAPESP. Interdisciplinary Research Activities in Electric Smart Grids. https://bv.fapesp.br/en/auxilios/97003/interdisciplinary-research-activities-in-electric-smart-grids/. Accessed on 05.01.2021.

[47] NB_POCCREI. Norwegian-Brazilian collaboration on Power Theories and Cooperative Control for Renewable Energy Integration. https://app.cristin.no/projects/show.jsf?id=568245. Accessed on 05.01.2021.

[48] H. Kim, J. Lee, S. Bahrami, and V. W. S. Wong, "Direct energy trading of microgrids in distribution energy market," *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 639–651, 2020.

[49] A. M. Alabdullatif, E. H. Gerding, and A. Perez-Diaz, "Market design and trading strategies for community energy markets with storage and renewable supply," *Energies*, vol. 13, p. 972, 2020.

[50] J. M. Zepter et al, "Prosumer integration in wholesale electricity markets: Synergies of peer-to-peer trade and residential storage," *Energy and Buildings*, vol. 184, pp. 163–176, 2019.

[51] T. Sousa et al, "Peer-to-peer and community-based markets: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 104, pp. 1367–378, 2019.

[52] Y. Han, K. Zhang, H. Li, E. A. A. Coelho, and J. M. Guerrero, "Mas-based distributed coordinated control and optimization in microgrid and microgrid clusters: A comprehensive overview," *IEEE Transactions on Power Electronics*, vol. 33, no. 8, pp. 6488–6508, 2018.

[53] L. Gkatzikis, I. Koutsopoulos, and T. Salonidis, "The role of aggregators in smart grid demand response markets," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 7, pp. 1247–1257, 2013.

[54] M. Park, J. Lee, and D. J. Won, "Demand response strategy of energy prosumer based on robust optimization through aggregator," *IEEE Access*, vol. 8, pp. 202 969–202 979, 2020.

[55] X. Zhou, L. Zhou, Y. Chen, J. M. Guerrero, A. Luo, W. Wu, and L. Yang, "A microgrid cluster structure and its autonomous coordination control strategy," *International Journal of Electrical Power & Energy Systems*, vol. 100, pp. 69–80, 2018.

[56] S. Li, J. Lian, A. J. Conejo, and W. Zhang, "Transactive energy systems: The market-based coordination of distributed energy resources," *IEEE Control Systems Magazine*, vol. 40, no. 4, pp. 26–52, 2020.

[57] M. Khorasany et al, "Transactive energy market for energy management in microgrids: The monash microgrid case study," *Energies*, vol. 13, pp. 1–13, 2020.

[58] O. Abrishambaf, F. Lezama, P. Faria, and Z. Vale, "Towards transactive energy systems: An analysis on current trends," *Energy Strategy Reviews*, vol. 26, p. 100418, 2019.

[59] S. M. Nosratabadi, R. Hooshmand, and E. Gholipour, "A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 341–363, 2017.

[60] T. L. Vandoorn, B. Zwaenepoel, J. D. M. De Kooning, B. Meersman, and L. Vandevelde, "Smart microgrids and virtual power plants in a hierarchical control structure," in *2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies*, 2011, pp. 1–7.

[61] T. Pinto et al, "Decision support for negotiations among microgrids using a multiagent architecture," *Energies*, vol. 11, p. 2526, 2018.

[62] Y. Zhao, J. Yu, M. Ban, Y. Liu, and Z. Li, "Privacy-preserving economic dispatch for an active distribution network with multiple networked microgrids," *IEEE Access*, vol. 6, pp. 38 802–38 819, 2018.

[63] P. Wu, W. Huang, N. Tai, and S. Liang, "A novel design of architecture and control for multiple microgrids with hybrid ac/dc connection," *Applied Energy*, vol. 210, pp. 1002–1016, 2018.

[64] H. Abedini, T. Caldognetto, P. Mattavelli, and P. Tenti, "Real-time validation of power flow control method for enhanced operation of microgrids," *Energies*, vol. 13, no. 5959, pp. 1–19, 2020.

[65] M. A. I. Martins, R. Fernandes, and M. L. Heldwein, "Proposals for regulatory framework modifications for microgrid insertion – the Brazil use case," *IEEE Access*, vol. 8, pp. 94 852–94 870, 2020.

[66] D. I. Brandao, W. M. Ferreira, A. M. S. Alonso, E. Tedeschi, and F. P. Marafão, "Optimal multiobjective control of low-voltage ac microgrids: Power flow regulation and compensation of reactive power and unbalance," *IEEE Transactions on Smart Grid*, vol. 11, no. 2, pp. 1239–1252, 2020.

[67] F. Rahimi and A. Ipakchi, "Using a transactive energy framework: Providing grid services from smart buildings," *IEEE Electrification Magazine*, vol. 4, no. 4, pp. 23–29, 2016.

[68] D. I. Brandao, T. Caldognetto, F. P. Marafão, M. G. Simões, J. A. Pomilio, and P. Tenti, "Centralized control of distributed single-phase inverters arbitrarily connected to three-phase four-wire microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 437–446, 2017.

[69] Q. Sun, J. Zhou, J. M. Guerrero, and H. Zhang, "Hybrid three-phase/single-phase microgrid architecture with power management capabilities," *IEEE Transactions on Power Electronics*, vol. 30, no. 10, pp. 5964–5977, 2015.

[70] D. Wang, J. Qiu, L. Reedman, K. Meng, and L. L. Lai, "Two-stage energy management for networked microgrids with high renewable penetration," *Applied Energy*, vol. 226, pp. 39–48, 2018.

[71] D. I. Brandao, L. S. Araujo, A. M. S. Alonso, G. L. dos Reis, E. V. Liberado, and F. P. Marafão, "Coordinated control of distributed three- and single-phase inverters connected to three-phase three-wire microgrids," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 4, pp. 3861–3877, 2020.

[72] S. Y. Mousazadeh Mousavi, A. Jalilian, M. Savaghebi, and J. M. Guerrero, "Autonomous control of current- and voltage-controlled dg interface inverters for reactive power sharing and harmonics compensation in islanded microgrids," *IEEE Transactions on Power Electronics*, vol. 33, no. 11, pp. 9375–9386, 2018.

[73] Y. Yu, Z. Cai, and Y. Huang, "Energy storage arbitrage in grid-connected microgrids under real-time market price uncertainty: A double-q learning approach," *IEEE Access*, vol. 8, pp. 54 456–54 464, 2020.

[74] M. Soshinskaya, W. H. Crijns-Graus, J. M. Guerrero, and J. C. Vasquez, "Microgrids: Experiences, barriers and success factors," *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 659–672, 2014.

[75] M. Eskandari, L. Li, M. H. Moradi, P. Siano, and F. Blaabjerg, "Optimal voltage regulator for inverter interfaced distributed generation units part i," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2813–2824, 2020.

[76] K. Mahmud, M. S. H. Nizami, J. Ravishankar, M. J. Hossain, and P. Siano, "Multiple home-to-home energy transactions for peak load shaving," *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1074–1085, 2020.

[77] P. Tenti and T. Caldognetto, "On microgrid evolution to local area energy network (e-lan)," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 1567–1576, 2019.

[78] G. V. B. Kumar and K. Palanisamy, "A review of energy storage participation for ancillary services in a microgrid environment," *Energies*, vol. 5, p. 63, 2020.

[79] R. Kabiri, D. G. Holmes, B. P. McGrath, and L. G. Meegahapola, "Lv grid voltage regulation using transformer electronic tap changing, with pv inverter reactive power injection," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 4, pp. 1182–1192, 2015.

[80] S. H. Toghroljerdi and J. Ostergaard, "Methods and strategies for overvoltage prevention in low voltage distribution systems with pv," *IET Renewable Power Generation*, vol. 11, no. 2, pp. 1–26, 2016.

[81] B. Olek and M. Wierzbowski, "Local energy balancing and ancillary services in low-voltage networks with distributed generation, energy storage, and active loads," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2499–2508, 2015.

[82] H. Akagi, "Control strategy and site selection of a shunt active filter for damping of harmonic propagation in power distribution systems," *IEEE Transactions on Power Delivery*, vol. 12, no. 1, pp. 354–363, 1997.

[83] J. Enslin and P. Heskes, "Harmonic interaction between a large number of distributed power inverters and the distribution network," *IEEE Transactions on Power Electronics*, vol. 19, no. 6, pp. 1586–1593, 2004.

[84] T. Wu, M. Rothleder, Z. Alaywan, and A. D. Papalexopoulos, "Pricing energy and ancillary services in integrated market systems by an optimal power flow," *IEEE Transactions on Power Systems*, vol. 19, no. 1, pp. 339–347, 2004.

[85] C. Chen, J. Wang, F. Qiu, and D. Zhao, "Resilient distribution system by microgrids formation after natural disasters," *IEEE Transactions on Smart Grid*, vol. 7, no. 2, pp. 958–966, 2016.

[86] J. Abdubannaev, S. YingYun, A. Xin, N. Makhamadjanova, and S. Rakhimov, "Investigate networked microgrids to enhance distribution network system resilience," in *2020 IEEE/IAS Industrial and Commercial Power System Asia (I CPS Asia)*, 2020, pp. 310–315.

[87] M. N. Ambia, K. Meng, W. Xiao, and Z. Y. Dong, “Nested formation approach for networked microgrid self-healing in islanded mode,” *IEEE Transactions on Power Delivery*, vol. 36, no. 1, pp. 452–464, 2021.

[88] G. Huang, J. Wang, C. Chen, J. Qi, and C. Guo, “Integration of preventive and emergency responses for power grid resilience enhancement,” *IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4451–4463, 2017.

[89] N. Karthikeyan, J. P. Radhakrishna, B. Bak-Jensen, and J. W. Simpson-Porco, “Predictive control of flexible resources for demand response in active distribution networks,” *IEEE Transactions on Power Systems*, vol. 34, no. 4, pp. 2957–2969, 2019.

[90] A. M. S. Alonso, D. I. Brandao, E. Tedeschi, and F. P. Marafão, “Resistive shaping of interconnected low-voltage microgrids operating under distorted voltages,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2021.

[91] Q. Jiang, M. Xue, and G. Geng, “Energy management of microgrid in grid-connected and stand-alone modes,” *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3380–3389, 2013.

[92] Y. C. C. Wong, C. S. Lim, M. D. Rotaru, A. Cruden, and X. Kong, “Consensus virtual output impedance control based on the novel droop equivalent impedance concept for a multi-bus radial microgrid,” *IEEE Transactions on Energy Conversion*, vol. 35, no. 2, pp. 1078–1087, 2020.

[93] S. D. Kermany, M. Joorabian, S. Deilami, and M. A. S. Masoum, “Hybrid islanding detection in microgrid with multiple connection points to smart grids using fuzzy-neural network,” *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 2640–2651, 2017.

[94] P. Monshizadeh, N. Monshizadeh, C. De Persis, and A. van der Schaft, “Output impedance diffusion into lossy power lines,” *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 1659–1668, 2019.

[95] T. Caldognetto, P. Tenti, A. Costabeber, and P. Mattavelli, “Improving microgrid performance by cooperative control of distributed energy sources,” *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 3921–3930, 2014.

[96] K. Strunz et al, “Benchmark systems for network integration of renewable and distributed energy resources,” CIGRE, Tech. Rep. CIGRE Task Force C6.04.02, July 2009.

[97] A. M. S. Alonso, L. C. Afonso, D. I. Brandao, E. Tedeschi, and F. P. Marafao, "Considerations on communication infrastructures for cooperative operation of smart inverters," in *2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC)*, 2019, pp. 1–6.

[98] R. Torquato, G. R. Tessmer Hax, W. Freitas, and A. B. Nassif, "Impact assessment of high-frequency distortions produced by pv inverters," *IEEE Transactions on Power Delivery*, pp. 1–1, 2020.

[99] Q. Liu, T. Caldognetto, and S. Buso, "Review and comparison of grid-tied inverter controllers in microgrids," *IEEE Transactions on Power Electronics*, vol. 35, no. 7, pp. 7624–7639, 2020.

[100] S. Buso, T. Caldognetto, and Q. Liu, "Analysis and experimental characterization of a large-bandwidth triple-loop controller for grid-tied inverters," *IEEE Transactions on Power Electronics*, vol. 34, no. 2, pp. 1936–1949, 2019.

[101] Y. Guan, Y. Wang, Y. Xie, Y. Liang, A. Lin, and X. Wang, "The dual-current control strategy of grid-connected inverter with lcl filter," *IEEE Transactions on Power Electronics*, vol. 34, no. 6, pp. 5940–5952, 2019.

[102] S. Buso and P. Mattavelli, *Digital Control in Power Electronics*, 2nd ed. Morgan & Claypool, 2015.

[103] P. Mattavelli and F. P. Marafao, "Repetitive-based control for selective harmonic compensation in active power filters," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 5, pp. 1018–1024, 2004.

[104] J. P. Bonaldo, H. K. Morales Paredes, and J. A. Pomilio, "Control of single-phase power converters connected to low-voltage distorted power systems with variable compensation objectives," *IEEE Transactions on Power Electronics*, vol. 31, no. 3, pp. 2039–2052, 2016.

[105] Q. Ouyang, Z. Wang, K. Liu, G. Xu, and Y. Li, "Optimal charging control for lithium-ion battery packs: A distributed average tracking approach," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 5, pp. 3430–3438, 2020.

[106] J. P. Bonaldo, J. A. O. Filho, A. M. S. Alonso, F. P. Marafao, and H. K. M. Paredes, "Modeling and control of a single-phase grid-connected inverter with lcl filter,," *IEEE Latin America Transactions*, vol. 100, no. 1, pp. 1–10, 2020.

[107] L. Zhou et al, "Harmonic voltage distortion damping method for parallel-connected lcl-type inverters in islanded operation," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 11, pp. 9032–9044, 2019.

[108] Y. Han, H. Li, P. Shen, E. A. A. Coelho, and J. M. Guerrero, “Review of active and reactive power sharing strategies in hierarchical controlled microgrids,” *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2427–2451, 2017.

[109] F. P. Marafão, A. M. d. S. Alonso, F. A. S. Gonçalves, D. I. Brandão, A. C. G. Martins, and H. K. Morales Paredes, “Trends and constraints on brazilian photovoltaic industry: Energy policies, interconnection codes, and equipment certification,” *IEEE Transactions on Industry Applications*, vol. 54, no. 5, pp. 4017–4027, 2018.

[110] H. M. A. Antunes et al, “A new multifunctional converter based on a series compensator applied to ac microgrids,” *International Journal of Electrical Power & Energy Systems*, vol. 102, pp. 160–170, 2018.

[111] M. Raeispour, H. Atrianfar, H. R. Baghaee, and G. B. Gharehpetian, “Resilient h∞ consensus-based control of autonomous ac microgrids with uncertain time-delayed communications,” *IEEE Transactions on Smart Grid*, vol. 11, no. 5, pp. 3871–3884, 2020.

[112] I. Ziouani et al, “Hierarchical control for flexible microgrid based on three-phase voltage source inverters operated in parallel,” *International Journal of Electrical Power & Energy Systems*, vol. 95, pp. 188–201, 2018.

[113] A. Chaouachi, R. M. Kamel, R. Andoulsi, and K. Nagasaka, “Multiobjective intelligent energy management for a microgrid,” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1688–1699, 2013.

[114] I. Serban, S. Céspedes, C. Marinescu, C. A. Azurdia-Meza, J. S. Gómez, and D. S. Hueichapan, “Communication requirements in microgrids: A practical survey,” *IEEE Access*, vol. 8, pp. 47 694–47 712, 2020.

[115] M. Saleh et al, “Impact of information and communication technology limitations on microgrid operation,” *Energies*, vol. 12, pp. 1–24, 2019.

[116] T. Caldognetto, S. Buso, P. Tenti, and D. I. Brandao, “Power-based control of low-voltage microgrids,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 4, pp. 1056–1066, 2015.

[117] D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “Autonomous active power control for islanded ac microgrids with photovoltaic generation and energy storage system,” *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 882–892, 2014.

[118] T. Vandoorn, B. Meersman, J. De Kooning, and L. Vandevelde, “Controllable harmonic current sharing in islanded microgrids: Dg units with programmable

resistive behavior toward harmonics," *IEEE Transactions on Power Delivery*, vol. 27, no. 2, pp. 831–841, 2012.

[119] I. Lorzadeh, H. A. Abyaneh, M. Savaghebi, and J. M. Guerrero, "A hierarchical control scheme for reactive power and harmonic current sharing in islanded microgrids," in *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*, 2015, pp. 1–10.

[120] F. Najafi, M. Hamzeh, and M. Fripp, "Unbalanced current sharing control in islanded low voltage microgrids," *Energies*, vol. 1, no. 10, pp. 1–22, 2018.

[121] Z. Afshar, M. Mollayousefi, S. M. T. Bathaee, M. T. Bina, and G. B. Gharehpetian, "A novel accurate power sharing method versus droop control in autonomous microgrids with critical loads," *IEEE Access*, vol. 7, pp. 89 466–89 474, 2019.

[122] Z. Cheng, J. Duan, and M. Chow, "To centralize or to distribute: That is the question: A comparison of advanced microgrid management systems," *IEEE Industrial Electronics Magazine*, vol. 12, no. 1, pp. 6–24, 2018.

[123] M. S. Padua, S. M. Deckmann, and F. P. Marafao, "Frequency-adjustable positive sequence detector for power conditioning applications," in *2005 IEEE 36th Power Electronics Specialists Conference*, 2005, pp. 1928–1934.

[124] A. V. Oppenheim and R. W. Schafer, *Discrete-Time Signal Processing*, 3rd ed. Upper Saddle River, NJ, USA: Prentice Hall Press, 2009.

[125] S. Park et al, "A current control scheme based on multiple synchronous reference frames for parallel hybrid active filter," in *Proceedings IPEMC 2000. Third International Power Electronics and Motion Control Conference (IEEE Cat. No.00EX435)*, vol. 1, 2000, pp. 218–223 vol.1.

[126] L. Xavier et al, "Adaptive current control strategy for harmonic compensation in single-phase solar inverters," *Electric Power Systems Reserach*, vol. 142, pp. 84–95, 2017.

[127] Q. Xu, J. Xiao, X. Hu, P. Wang, and M. Y. Lee, "A decentralized power management strategy for hybrid energy storage system with autonomous bus voltage restoration and state-of-charge recovery," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 9, pp. 7098–7108, 2017.

[128] A. M. S. Alonso, D. I. Brandao, F. P. Marafão, and E. Tedeschi, "Coordinated control of parallel power conditioners synthesizing resistive loads in single-phase ac microgrids," in *2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe)*, 2019, pp. 1–9.

[129] E. V. Liberado, J. A. Pomilio, A. M. S. Alonso, E. Tedeschi, F. P. Marafão, and J. F. Guerreiro, "Three/four-leg inverter current control based on generalized symmetrical components," in *2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2018, pp. 1–7.

[130] A. M. S. Alonso, D. I. Brandao, E. Tedeschi, and F. P. Marafão, "Distributed selective harmonic mitigation and decoupled unbalance compensation by coordinated inverters in three-phase four-wire low-voltage networks," *Electric Power Systems Research*, vol. 186, pp. 1–14, 2020.

[131] A. M. S. Alonso, L. O. Arenas, R. T. Hock Jr., H. Guillardi Jr., H. K. M. Paredes, F. A. S. Goncalves, and F. P. Marafão, "Experimental implementation of a single-phase microgrid comprising multiple inverters to validate coordinated control strategies," in *14th IEEE International Conference on Industry Applications (INDUSCON)*, 2021, pp. 7–11.

[132] M. Depenbrock, "Quantities of a multiterminal circuit determined on the basis of Kirchhoff's laws," *European Transactions on Electrical Power*, vol. 8, no. 4, pp. 249–257, 1998.

[133] J. Arrillaga and N. R. Watson, *Power System Harmonics*, 2nd ed. John Wiley and Sons Ltd, 2003.

[134] H. Akagi, "New trends in active filters for power conditioning," *IEEE Transactions on Industry Applications*, vol. 32, no. 6, pp. 1312–1322, 1996.

[135] L. Chen, X. Xu, L. Yao, and Q. Xu, "Study of a distribution line overload control strategy considering the demand response," *Electric Power Components and Systems*, vol. 42, no. 9, pp. 970–983, 2014.

[136] G. Cavraro, T. Caldognetto, R. Carli, and P. Tenti, "A master/slave approach to power flow and overvoltage control in low-voltage microgrids," *Energies*, vol. 12, no. 14, pp. 1–22, 2019.

[137] D. Prudhviraj, P. B. S. Kiran, and N. M. Pindoriya, "Stochastic energy management of microgrid with nodal pricing," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 1, pp. 102–110, 2020.

[138] U. Karki, D. Gunasekaran, and Fang Zheng Peng, "Reactive compensation of overhead ac transmission lines using underground power cables," in *2015 IEEE Power Energy Society General Meeting*, 2015, pp. 1–5.

[139] M. Ganjian-Aboukheili, M. Shahabi, Q. Shafiee, and J. M. Guerrero, "Seamless transition of microgrids operation from grid-connected to islanded mode," *IEEE Transactions on Smart Grid*, vol. 11, no. 3, pp. 2106–2114, 2020.

[140] M. Amin and Q. Zhong, "Resynchronization of distributed generation based on the universal droop controller for seamless transfer between operation modes," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 9, pp. 7574–7582, 2020.

[141] T. L. Vandoorn, B. Meersman, J. D. M. De Kooning, and L. Vandevelde, "Transition from islanded to grid-connected mode of microgrids with voltage-based droop control," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2545–2553, 2013.

[142] S. D'Arco and J. A. Suul, "Equivalence of virtual synchronous machines and frequency-droops for converter-based microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 394–395, 2014.

[143] M. A. Awal and I. Husain, "Unified virtual oscillator control for grid-forming and grid-following converters," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2020.

[144] C. Li, C. Cao, Y. Cao, Y. Kuang, L. Zeng, and B. Fang, "A review of islanding detection methods for microgrid," *Renewable and Sustainable Energy Reviews*, vol. 35, pp. 211–220, 2014.

[145] P. Tenti, T. Caldognetto, S. Buso, and D. I. Brandao, "Control of utility interfaces in low-voltage microgrids," *Brazilian Journal of Power Electronics (SOBRAEP)*, vol. 20, no. 4, pp. 373 – 382, 2015.

[146] J. Kwon, S. Yoon, and S. Choi, "Indirect current control for seamless transfer of three-phase utility interactive inverters," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 773–781, 2012.

[147] D. I. Brandao, "Coordinated power-based control and utility interface converter in low voltage microgrids," Ph.D. dissertation, University of Campinas, Campinas, 9 2015.

[148] Z. Zeng, R. Zhao, and H. Yang, "Coordinated control of multi-functional grid-tied inverters using conductance and susceptance limitation," *IET Power Electronics*, vol. 7, no. 7, pp. 1821–1831, 2014.

[149] A. H. Yazdavar, M. A. Azzouz, and E. F. El-Saadany, "A novel decentralized control scheme for enhanced nonlinear load sharing and power quality in islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 29–39, 2019.

[150] F. Dorfler, J. W. S. Porco, and F. Bullo, "Breaking the hierarchy: Distributed control and economic optimality in microgrids," *IEEE Transactions on Control of Network Systems*, vol. 3, no. 3, pp. 241–253, 2016.

[151] P. Sreekumar and V. Khadkikar, "Direct control of the inverter impedance to achieve controllable harmonic sharing in the islanded microgrid," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 1, pp. 827–837, 2017.

[152] X. Wang, Y. W. Li, F. Blaabjerg, and P. C. Loh, "Virtual-impedance-based control for voltage-source and current-source converters," *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 7019–7037, 2015.

[153] F. Gothner, O. Midtgård, R. Torres-Olguin, and J. Roldan-Perez, "Virtual impedance design for power quality and harmonic sharing improvement in microgrids," in *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2019, pp. 1–7.

[154] A. Micallef, M. Apap, C. Spiteri-Staines, J. M. Guerrero, and J. C. Vasquez, "Reactive power sharing and voltage harmonic distortion compensation of droop controlled single phase islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1149–1158, 2014.

[155] W. Deng, N. Dai, K. W. Lao, and J. M. Guerrero, "A virtual-impedance droop control for accurate active power control and reactive power sharing using capacitive-coupling inverters," *IEEE Transactions on Industry Applications*, vol. 56, no. 6, pp. 6722–6733, 2020.

[156] A. Adib and B. Mirafzal, "Virtual inductance for stable operation of grid-interactive voltage source inverters," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6002–6011, 2019.

[157] T. E. Nunez-Zuniga and J. A. Pomilio, "Shunt active power filter synthesizing resistive loads," *IEEE Transactions on Power Electronics*, vol. 17, no. 2, pp. 273–278, 2002.

[158] R. Hiremath and T. Moger, "Comprehensive review on low voltage ride throughcapability of wind turbine generators," *International Transactions on Electrical Energy Systems*, vol. 30, pp. 1–39, 2020.

[159] H. Tian, F. Gao, C. Ma, G. He, and G. Li, "A review of low voltage ride-through techniques for photovoltaic generation systems," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2014, pp. 1566–1572.

[160] N. Bottrell and T. C. Green, "Comparison of current-limiting strategies during fault ride-through of inverters to prevent latch-up and wind-up," *IEEE Transactions on Power Electronics*, vol. 29, no. 7, pp. 3786–3797, 2014.

[161] M. S. Witherden, R. Rayudu, and R. Rigo-Mariani, "The influence of nonlinear loads on the power quality of the new zealand low voltage electrical power distribution network," in *2010 20th Australasian Universities Power Engineering Conference*, 2010, pp. 1–6.

[162] A. T. Procopiou and L. F. Ochoa, "Voltage control in pv-rich lv networks without remote monitoring," *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 1224–1236, 2017.

[163] Z. Xin, P. Mattavelli, W. Yao, Y. Yang, F. Blaabjerg, and P. C. Loh, "Mitigation of grid-current distortion for lcl-filtered voltage-source inverter with inverter-current feedback control," *IEEE Transactions on Power Electronics*, vol. 33, no. 7, pp. 6248–6261, 2018.

[164] Z. Shuai et al, "Microgrid stability: Classification and a review," *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 167–179, 2016.

[165] R. Majumder, "Some aspects of stability in microgrids," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3243–3252, 2013.

[166] E. F. Alves, G. Bergna, D. I. Brandao, and E. Tedeschi, "Sufficient conditions for robust frequency stability of ac power systems," *IEEE Transactions on Power Systems*, pp. 1–1, 2020.

[167] A. K. Singh, R. Singh, and B. C. Pal, "Stability analysis of networked control in smart grids," *IEEE Transactions on Smart Grid*, vol. 6, no. 1, pp. 381–390, 2015.

[168] M. N. Alam, S. Chakrabarti, and A. Ghosh, "Networked microgrids: State-of-the-art and future perspectives," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 3, pp. 1238–1250, 2019.

[169] K. Ogata, *Discrete-time Control Systems*, 2nd ed. Prentice-Hall, 1995.

[170] A. Angioni et al, "Coordinated voltage control in distribution grids with lte based communication infrastructure," in *2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)*, 2015, pp. 2090–2095.

[171] H. Han, X. Hou, J. Yang, J. Wu, M. Su, and J. M. Guerrero, "Review of power sharing control strategies for islanding operation of ac microgrids," *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 200–215, 2016.

[172] T. J. Mary and P. Rangarajan, "Delay-dependent stability analysis of microgrid with constant and time-varying communication delays," *Electric Power Components and Systems*, vol. 44, no. 13, pp. 1441–1452, 2016.

[173] K. C. Budka, J. G. Deshpande, and M. Thottan, *Communication Networks for Smart Grids*, 1st ed. Springer, 2014.

[174] B. Francis et al., "Sunspec plant information exchange: Sunspec alliance interoperability specification," Sunspec Alliance, Tech. Rep. Draft, July 2015.

[175] Z. Peng, J. Wang, D. Bi, Y. Wen, Y. Dai, X. Yin, and Z. J. Shen, "Droop control strategy incorporating coupling compensation and virtual impedance for microgrid application," *IEEE Transactions on Energy Conversion*, vol. 34, no. 1, pp. 277–291, 2019.

[176] T. L. Vandoorn, J. D. M. De Kooning, B. Meersman, J. M. Guerrero, and L. Vandevelde, "Automatic power-sharing modification of p/ v droop controllers in low-voltage resistive microgrids," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 2318–2325, 2012.

[177] P. Jintakosonwit, H. Fujita, H. Akagi, and S. Ogasawara, "Implementation and performance of cooperative control of shunt active filters for harmonic damping throughout a power distribution system," *IEEE Transactions on Industry Applications*, vol. 39, no. 2, pp. 556–564, 2003.

[178] S. A. R. Konakalla, A. Valibeygi, and R. A. de Callafon, "Microgrid dynamic modeling and islanding control with synchrophasor data," *IEEE Transactions on Smart Grid*, vol. 11, no. 1, pp. 905–915, 2020.

[179] M. S. Golsorkhi, D. D. Lu, and J. M. Guerrero, "A gps-based decentralized control method for islanded microgrids," *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 1615–1625, 2017.

[180] G. Yang, K. E. Martin, and J. Østergaard, "Investigation of pmu performance under tve criterion," in *2010 5th International Conference on Critical Infrastructure (CRIS)*, 2010, pp. 1–7.

[181] O. B. Fosso, M. Molinas, K. Sand, and G. H. Coldevin, "Moving towards the smart grid: The norwegian case," in *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, 2014, pp. 1861–1867.

[182] F. Yang, X. Feng, and Z. Li, "Advanced microgrid energy management system for future sustainable and resilient power grid," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7251–7260, 2019.

[183] J. He, B. Liang, Y. W. Li, and C. Wang, "Simultaneous microgrid voltage and current harmonics compensation using coordinated control of dual-interfacing converters," *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 2647–2660, 2017.

[184] H. Pezeshki, P. J. Wolfs, and G. Ledwich, "Impact of high pv penetration on distribution transformer insulation life," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1212–1220, 2014.

[185] D. J. Hogan, F. J. Gonzalez-Espin, J. G. Hayes, G. Lightbody, and R. Foley, "An adaptive digital-control scheme for improved active power filtering under distorted grid conditions," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 988–999, 2018.

[186] A. Arguello, R. Torquato, W. Freitas, and A. Padilha Feltrin, "A graphical method to assess component overload due to harmonic resonances in wind parks," *IEEE Transactions on Power Delivery*, pp. 1–1, 2020.

[187] S. Devassy and B. Singh, "Performance analysis of solar pv array and battery integrated unified power quality conditioner for microgrid systems," *IEEE Transactions on Industrial Electronics*, pp. 1–1, 2020.

[188] Y. Chen, J. M. Guerrero, Z. Shuai, Z. Chen, L. Zhou, and A. Luo, "Fast reactive power sharing, circulating current and resonance suppression for parallel inverters using resistive-capacitive output impedance," *IEEE Transactions on Power Electronics*, vol. 31, no. 8, pp. 5524–5537, 2016.

[189] M. Depenbrock, "The fbd-method, a generally applicable tool for analyzing power relations," *IEEE Transactions on Power Systems*, vol. 8, no. 2, pp. 381–387, 1993.

[190] L. S. Czarnecki, "What is wrong with the Budeanu concept of reactive and distortion power and why it should be abandoned," *IEEE Transactions on Instrumentation and Measurement*, vol. 36, no. 3, pp. 834–837, 1987.

[191] S. Fryze, "Active, reactive and apparent power in circuits with nonsinusoidal voltage and current," *Przegl. Elektrotech*, vol. 7, pp. 193–203, 1931.

[192] J. H. Braslavsky, L. D. Collins, and J. K. Ward, "Voltage stability in a grid-connected inverter with automatic volt-watt and volt-var functions," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 84–94, 2019.

[193] A. Anzalchi, A. Sundararajan, A. Moghadasi, and A. Sarwat, "High-penetration grid-tied photovoltaics: Analysis of power quality and feeder voltage profile," *IEEE Industry Applications Magazine*, vol. 25, no. 5, pp. 83–94, 2019.

[194] A. Hoke, J. Giraldez, B. Palmintier, E. Ifuku, M. Asano, R. Ueda, and M. Symko-Davies, "Setting the smart solar standard: Collaborations between hawaiian electric and the national renewable energy laboratory," *IEEE Power and Energy Magazine*, vol. 16, no. 6, pp. 18–29, 2018.

[195] S. H. Toghroljerdi and J. Ostergaard, “Prevention of distribution network overvoltage by adaptive droop-based active and reactive power control of pv systems,” *Electric Power Systems Research*, vol. 113, pp. 313–327, 2016.

[196] S. Pukhrem, M. Basu, M. F. Conlon, and K. Sunderland, “Enhanced network voltage management techniques under the proliferation of rooftop solar pv installation in low-voltage distribution network,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 2, pp. 681–694, 2017.

[197] K. Baker, A. Bernstein, E. Dall’Anese, and C. Zhao, “Network-cognizant voltage droop control for distribution grids,” *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 2098–2108, 2018.

[198] M. Juamperez, G. Yang, and S. B. Kjær, “Voltage regulation in lv grids by coordinated volt-var control strategies,” *Journal of Modern Power Systems and Clean Energy*, vol. 2, no. 4, pp. 319–328, 2014.

[199] T. T. Mai, n. Haque, H. T. Vo, and P. H. Nguyen, “Methods and strategies for overvoltage prevention in low voltage distribution systems with pv,” *IET Renewable Power Generation*, vol. 2019, no. 18, pp. 5007–5011, 2019.

[200] G. Cavraro, T. Caldognetto, R. Carli, and P. Tenti, “A master/slave approach to power flow and overvoltage control in low-voltage microgrids,” *Energies*, vol. 12, p. 2760, 2019.

[201] Y. Wang, P. Zhang, W. Li, W. Xiao, and A. Abdollahi, “Online overvoltage prevention control of photovoltaic generators in microgrids,” *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2071–2078, 2012.

[202] H. Lee, K. Yoon, J. Shin, J. Kim, and S. Cho, “Optimal parameters of volt–var function in smart inverters for improving system performance,” *Energies*, vol. 13, p. 2294, 2020.

[203] Y. Yang, H. Wang, and F. Blaabjerg, “Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements,” *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 4065–4076, 2014.

[204] L. De Oro Arenas, G. d. A. e Melo, and C. A. Canesin, “A methodology for power quantities calculation applied to an FPGA-based smart-energy meter,” *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–11, 2021.

[205] S. Alyami, Y. Wang, C. Wang, J. Zhao, and B. Zhao, “Adaptive real power capping method for fair overvoltage regulation of distribution networks with high penetration of pv systems,” *IEEE Transactions on Smart Grid*, vol. 5, no. 6, pp. 2729–2738, 2014.

[206] F. H. M. Rafi, M. J. Hossain, M. S. Rahman, and S. Taghizadeh, "An overview of unbalance compensation techniques using power electronic converters for active distribution systems with renewable generation," *Renewable and Sustainable Energy Reviews*, vol. 125, p. 109812, 2020.

[207] A. S. Vijay, S. Doolla, and M. C. Chandorkar, "Unbalance mitigation strategies in microgrids," *IET Power Electronics*, vol. 13, no. 9, pp. 1687–1710, 2020.

[208] D. V. Bozalakov, J. Laveyne, J. Desmet, and L. Vandelvelde, "Overvoltage and voltage unbalance mitigation in areas with high penetration of renewable energy resources by using the modified three-phase damping control strategy," *Electric Power Systems Research*, vol. 168, pp. 283–294, 2019.

[209] M. Savaghebi, A. Jalilian, J. C. Vasquez, and J. M. Guerrero, "Autonomous voltage unbalance compensation in an islanded droop-controlled microgrid," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1390–1402, 2013.

[210] J. Liu, Y. Miura, and T. Ise, "Cost-function-based microgrid decentralized control of unbalance and harmonics for simultaneous bus voltage compensation and current sharing," *IEEE Transactions on Power Electronics*, vol. 34, no. 8, pp. 7397–7410, 2019.

[211] E. Espina, R. Cárdenas-Dobson, M. Espinoza-B., C. Burgos-Mellado, and D. Sáez, "Cooperative regulation of imbalances in three-phase four-wire microgrids using single-phase droop control and secondary control algorithms," *IEEE Transactions on Power Electronics*, vol. 35, no. 2, pp. 1978–1992, 2020.

[212] Z. Hou, Y. Sun, W. Yuan, H. Han, C. Hong, and J. M. Guerrero, "Conventional p-ω/q-v droop control in highly resistive line of low-voltage converter-based ac microgrid," *Energies*, vol. 9, p. 943, 2016.

[213] C. Burgos-Mellado, R. Cárdenas, D. Sáez, A. Costabeber, and M. Sumner, "A control algorithm based on the conservative power theory for cooperative sharing of imbalances in four-wire systems," *IEEE Transactions on Power Electronics*, vol. 34, no. 6, pp. 5325–5339, 2019.

[214] T. D. C. Busarello, A. Mortezaei, A. Péres, and M. G. Simões, "Application of the conservative power theory current decomposition in a load power-sharing strategy among distributed energy resources," *IEEE Transactions on Industry Applications*, vol. 54, no. 4, pp. 3771–3781, 2018.

[215] F. P. Marafao, D. I. Brandao, F. A. S. Gonçalves, and H. K. M. Paredes, "Decoupled reference generator for shunt active filters using the conservative power

theory," *Journal of Control, Automation and Electrical Systems*, vol. 24, p. 522–534, 2013.

[216] D. I. Brandao, H. Guillardi, H. K. Morales-Paredes, F. P. Marafão, and J. A. Pomilio, "Optimized compensation of unwanted current terms by ac power converters under generic voltage conditions," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 12, pp. 7743–7753, 2016.

[217] A. M. S. Alonso, B. R. Pereira Jr., D. I. Brandao, and F. P. Marafao, "Optimized exploitation of ancillary services: Compensation of reactive, unbalance and harmonic currents based on particle swarm optimization," *IEEE Latin America Transactions*, vol. 100, no. 1, pp. 1–12, 2020.

[218] T. C. Monteiro et al, "Dynamic voltage restorer development and testing," in *XI Brazilian Power Electronics Conference*, 2011, pp. 1–1.

[219] G. Carpinelli, F. Mottola, D. Proto, and A. Russo, "A multi-objective approach for microgrid scheduling," *IEEE Transactions on Smart Grid*, vol. 8, no. 5, pp. 2109–2118, 2017.

[220] M. N. Costa, F. Gonzalez-Longatt, D. Topic, and M. A. Andrade, "Optimal microgrid–interactive reactive power management for day–ahead operation," *Energies*, vol. 14, p. 1275, 2021.

[221] A. H. Fathima and K. Palanisamy, "Optimization in microgrids with hybrid energy systems – a review," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 431–446, 2015.

[222] A. A. Anderson and S. Suryanarayanan, "Review of energy management and planning of islanded microgrids," *CSEE Journal of Power and Energy Systems*, vol. 6, no. 2, pp. 329–343, 2020.

[223] B. Khan and P. Singh, "Selecting a meta-heuristic technique for smart microgrid optimization problem: A comprehensive analysis," *IEEE Access*, vol. 5, pp. 13 951–13 977, 2017.

[224] L. I. Avila, L. E. Castanon, A. V. Martinez, and Y. Zhang, "A review of optimal control techniques applied to the energy management and control of microgrids," *Procedia Computer Science*, vol. 52, pp. 780–787, 2015.

[225] J. Alshehri and M. Khalid, "Power quality improvement in microgrids under critical disturbances using an intelligent decoupled control strategy based on battery energy storage system," *IEEE Access*, vol. 7, pp. 147 314–147 326, 2019.

[226] D. M. Ferreira, D. I. Brandao, G. Bergna-Diaz, E. Tedeschi, and S. M. Silva, "Distributed control strategy for low-voltage three-phase four-wire microgrids: Consensus power-based control," *IEEE Transactions on Smart Grid*, pp. 1–1, 2021.

[227] P. Tenti and P. Mattavelli, "A time domain approach to power term definitions under non sinusoidal conditions," *L'Energia Elettrica*, vol. 81, 2004.

[228] D. De Roover and O. H. Bosgra, "An internal-model-based framework for the analysis and design of repetitive and learning controllers," in *Proceedings of the 36th IEEE Conference on Decision and Control*, vol. 4, 1997, pp. 3765–3770 vol.4.