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A thesis in fulfilment of the requirements for the degree of

Doctor of Philosophy

School of Electrical Engineering and Telecommunications

Faculty of Engineering

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April 2023

I, AUTHORNAME confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

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Acknowledgements

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Abbreviations and Nomenclature

AC	**A**lternating **C**urrent
AEMC	**A**ustralian **E**nergy **M**arket **C**ommission
AEMO	**A**ustralian **E**nergy **M**arket **O**perator
AER	**A**ustralian **E**nergy **R**egulator
AGC	**A**utomatic **g**eneration **c**ontrol
BESS	**B**attery **e**nergy **s**torage **s**ystems
BRP	**B**alancing **r**esponsible **p**arty
BSP	**B**alancing **s**ervice **p**rovider
DC	**D**irect **c**urrent
DR	**D**emand **r**esponse
ENSTO-E	**E**uropean **N**etwork of **T**ransmission **S**ystem **O**perators for **E**lectricity
ESB	**E**nergy **S**ecurity **B**oard
IBR	**I**nverter-**b**ased **r**esources
ISO/RTO	**I**ndependent **S**ystem **O**perator/**R**egional **T**ransmission **O**rganisation
FCS	**F**requency **c**ontrol **s**ervices
FCAS	**F**requency **C**ontrol **A**ncillary **S**ervices
FERC	**F**ederal **E**nergy **R**egulatory **C**ommission
FFR	**F**ast **f**requency **r**esponse
Hz	Hertz

mHz	Millihertz
MW	Megawatts
NEM	**N**ational **E**lectricity **M**arket
NER	**N**ational **E**lectricity **R**ules
NOFB	**N**ormal **o**perating **f**requency **b**and
NSW	**N**ew **S**outh **W**ales
OFGS	**O**ver-**f**requency **g**eneration **s**hedding
PFR	**P**rimary **f**requency **r**esponse
PV	**P**hoto**v**oltaic
QLD	Queensland
RoCoF	**R**ate **o**f **c**hange **o**f **f**requency
SA	**S**outh **A**ustralia
SFR	**S**econdary **f**requency **r**esponse
SO	**S**ystem **o**perator
TAS	Tasmania
TFR	**T**ertiary **f**requency **r**esponse
TNSP	**T**ransmission **N**etwork **S**ervice **P**rovider
TSO	**T**ransmission **S**ystem **O**perator
UFLS	**U**nder-**f**requency **l**oad **s**hedding
UK	**U**nited **K**ingdom
US	**U**nited **S**tates
UFLS	**U**nder-**f**requency **l**oad **s**hedding
VIC	Victoria
VRE	**V**ariable **r**enewable **e**nergy

Chapter 1

Introduction, with a citation

1.1 Background

This is the introduction. Quisque finibus aliquet cursus. Integer in pellentesque tellus. Duis eu dignissim nulla, a porttitor enim. Quisque vehicula leo non ultrices finibus. Duis vehicula quis sem sit amet sollicitudin. Integer neque est, pharetra et auctor vel, iaculis interdum lectus.

To include a citation to the text, just add the citation key shown in the references.bib file. The style of the citation is determined by the ref_format.csl file. For example, in The Living Sea you can find pictures of the Calypso (**Cousteau1963?**).

In neque mauris, maximus at sapien a, iaculis dignissim justo. Aliquam erat volutpat. Praesent varius risus auctor est ultricies, sit amet consequat nisi laoreet. Suspendisse non est et mauris pharetra sagittis non porta justo. Praesent malesuada metus ut sapien sodales ornare.

1.2 The middle bit

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1.2.1 Subsection of the middle bit

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1.3 Summary of chapters

This is a brief outline of what went into each chapter, and a section which shows how to reference headers (which are labelled automatically for you). This chapter, Chapter 1, shows how to use citations and how to reference section headers. Chapter 2 shows how use and reference equations. Chapter **??** shows how to use and reference code. Chapter 4 shows how to use, reference, and resize pdf and jpg figures. Chapter 5 shows how to use and reference tables. Chapter 6 is truly revolutionary (but shows nothing functional). **Appendix 1** shows how to add chapters which are not numbered, and has to be referenced manually, as does **Appendix 2**. See the base `README.md` for how References are handled - leave `*_references.md` alone, and provide it to `pandoc` last.

Proin faucibus nibh sit amet augue blandit varius[1].

[1] The term *balancing services* is used in European systems, whereas the term *operating reserves* is widely used in North America.

Chapter 2

Literature review, with maths

2.1 Introduction

This is the introduction. Duis in neque felis. In hac habitasse platea dictumst. Cras eget rutrum elit. Pellentesque tristique venenatis pellentesque. Cras eu dignissim quam, vel sodales felis. Vestibulum efficitur justo a nibh cursus eleifend. Integer ultrices lorem at nunc efficitur lobortis.

2.2 The middle

This is the literature review. Nullam quam odio, volutpat ac ornare quis, vestibulum nec nulla. Aenean nec dapibus in mL/min^{-1}. Mathematical formula can be inserted using Latex and can be automatically numbered:

$$f(x) = ax^3 + bx^2 + cx + d \tag{2.1}$$

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Later on in the text, you can reference Equation 2.1 and its mind-blowing ramifications. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Sed faucibus pulvinar volutpat. Ut semper fringilla erat non dapibus. Nunc vitae felis eget purus placerat finibus laoreet ut nibh.

2.3 A complicated math equation

The following raw text in markdown behind Equation 2.2 shows that you can fall back on LaTeXif it is more convenient for you. Note that this will only be rendered in `thesis.pdf`

$$\begin{aligned} \hat{\theta}_g = \underset{\theta_g}{\operatorname{argmin}} \Bigg\{ - \sum_{n=1}^{N} \Big(1 - \mathbb{1}[f(\boldsymbol{x}^{(n)})] \Big) \log f \Big(& \boldsymbol{x}^{(n)} \\ & + g(\boldsymbol{x}^{(n)}; \theta_g) \Big) + \lambda | g(\boldsymbol{x}^{(n)}; \theta_g) |_2 \Bigg\} , \end{aligned} \tag{2.2}$$

2.4 Conclusion

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Chapter 3

Frequency control arrangements: insights from the National Electricity Market

3.1 Link to thesis

This is the introduction. Nam mollis congue tortor, sit amet convallis tortor mollis eget. Fusce viverra ut magna eu sagittis. Vestibulum at ultrices sapien, at elementum urna. Nam a blandit leo, non lobortis quam. Aliquam feugiat turpis vitae tincidunt ultricies. Mauris ullamcorper pellentesque nisl, vel molestie lorem viverra at.

3.2 Abstract

For restructured electricity industries undergoing energy transition, designing effective and efficient frequency control arrangements is a complex and ongoing task that requires appropriate configuration of controllers, generator technical connection requirements, market arrangements and wider policy settings. In this paper, we provide an overview and assessment of these arrangements in Australia's National Electricity Market - a useful case study given its long-standing frequency control ancillary services markets, yet recent challenges in maintaining secure frequency control. We assess the performance of these evolving arrangements in delivering improved frequency control outcomes, with particular regard to growing renewable penetrations and evident tensions between mandatory requirements and market-based incentives. Based on this assessment, we draw out four key insights on designing frequency control arrangements as power system capabilities and needs change: 1) Understanding control action interactions, 2) Implementing efficient price formation and cost-allocation mechanisms, 3) Monitoring and assessing service provision to better align participant remuneration with service quality, and 4) Considering both regulatory and market mechanisms and their consequences and interactions. In particular, we discuss the trade-offs between effective and efficient outcomes, and provide arguments for more robust and forward-looking frequency control arrangements during energy transition.

3.3 Introduction

As a consequence of growing momentum to address global warming and continually declining technology costs, many power systems around the world are undergoing an energy transition in which significant capacity additions of variable renewable energy (VRE) and other inverter-based resources (IBR) are being accompanied by the progressive retirement of existing fossil fuel generation (International Energy Agency, 2021). Such power systems are currently experiencing or expected to soon experience high instantaneous penetrations of VRE (i.e. beyond 50% of grid demand being met by VRE at any given time), which can pose technical challenges to the stable and secure operation of a power system (Kenyon et al., 2020; Kroposki et al., 2017; Meegahapola et al., 2021). While several of these challenges have technological solutions of various maturities, configuring mechanisms in an effective and efficient manner across power system design layers, which span from how resources are controlled to how grid codes and markets are designed, remains an open and significant challenge.

In this article, we focus on one aspect of power system security: control of AC frequency. Maintaining frequency near the nominal value of a power system (either 50 or 60 Hz) is contingent on the ongoing balance of active power supply and demand within a synchronous area (Grainger, 1994). Power system frequency deviations are a consequence of instantaneous supply-demand imbalances, which typically occur as a result of system variability (predictable changes in supply or demand, such as fluctuations and ramps of generation or load) and uncertainty (unpredicted changes in supply or demand, such as forecast errors or unplanned outages) (Ela et al., 2011). System operators (SOs) achieve short-term active power balancing using reserve capacity. Whilst there are many names for these reserves[1], this article will focus on a common subset that responds to and mitigates frequency deviations over short timeframes (milliseconds to minutes). We will refer to such reserves as *Frequency Control Services* (FCS). If FCS are insufficient or inadequate, the system frequency may deviate beyond acceptable system limits and lead to equipment damage, load shedding, generator trips and cascading failures that lead to blackouts (Kirby et al., 2002; Ulbig et al., 2014).

In electricity industries with competitive markets for energy and FCS, frequency control arrangements consist of control, regulatory and market-based mechanisms (Mancarella and Billimoria, 2021). Control mechanisms specify the technical requirements for FCS. Regulatory and market-based mechanisms are used by the SO to:

1. Mandate or incentivise participant behaviour in the energy market that facilitates system balancing. This includes enforcing dispatch compliance or penalising participant portfolio imbalances; and
2. Procure FCS from capable resources (i.e. generators, loads and network elements).

Regulatory FCS procurement mechanisms are often mandatory and include equipment standards, connection requirements and SO intervention, whereas market-based FCS procurement mechanisms are often voluntary and include remunerative schemes and contract or spot markets. Together, these mechanisms dictate the physical effectiveness and productive, dynamic, price formation and cost-allocation efficiencies of FCS provision and procurement. Well-designed arrangements should be effective and efficient, where *effectiveness*

[1]The term *balancing services* is used in European systems, whereas the term *operating reserves* is widely used in North America.

entails sufficient and robust frequency response to meet physical power system requirements and *efficiency* relates to frequency response being provided at low cost, both now and into the future (Y. Rebours et al., 2007; van der Veen and Hakvoort, 2016).

As power systems transition towards higher instantaneous penetrations of VRE and IBR, SOs are likely to face the following challenges to short-term system balancing that may require existing frequency control arrangements to be revisited:

- VRE adds variability and uncertainty to a power system, particularly if similar technologies are situated within close proximity of one another (i.e. correlated production and/or forecast errors) (Australian Energy Market Operator, 2020a; Keeratimahat et al., 2021). Furthermore, unless an appropriate response is incorporated and enabled in their control systems, VRE and other IBR do not provide FCS. In jurisdictions that do not require, incentivise or allow VRE and IBR to provide FCS, the displacement of synchronous machines in dispatch has led to lower availabilities of resources that provide FCS (Australian Energy Market Operator, 2020b; Denholm et al., 2020; Milano et al., 2018) .
- In jurisdictions with competitive markets for energy and FCS, there is a tension between achieving economically efficient markets and the redundancy, certainty and control afforded to the SO. While the societal and economic costs of power system failure are often very large, it may be difficult for the SO to justify the cost of mitigation measures when they are ongoing or significant and when the joint probability of events or failures is low. The uncertainties associated with energy transition and the impacts

> of global warming are likely to present additional challenges. Power system security measures may need to be implemented rapidly and be both robust to a range of futures and resilient in the face of shocks, such as severe weather events (Eggleston et al., 2021; Prakash et al., 2021).

In this paper, we provide insights and recommendations on designing more effective and efficient frequency control arrangements based on experience from the Australian National Electricity Market (NEM). The NEM is currently experiencing relatively high system-wide instantaneous VRE penetrations (just over 60% in 2021) and is expected to experience penetrations as high as 75-100% by 2025 (Australian Energy Market Operator, 2021a, 2021b). Though the NEM's frequency control arrangements were once arguably world-leading (Riesz et al., 2015; Thorncraft and Outhred, 2007), the speed at which system capabilities and needs are changing and the removal of mandatory requirements in 2001 as a part of a paradigm shift from obligation to remuneration for FCS have exposed design issues. In attempting to address these issues, the NEM's rule makers have placed FCS obligations on generators and transmission network operators and have undertaken reforms to the NEM's energy and FCS markets, including introducing a new market to procure emergency fast frequency response (FFR) from IBR. Whilst the NEM is an electrically-isolated power system with a relatively simple energy-only market, the insights and recommendations from this paper are likely to be relevant to other power systems and interconnections as their existing conventional generation retires and VRE deployment levels increase.

This paper offers three contributions to the literature. First, we provide a high-level overview and comparison of the key features of frequency control arrangements in North America and Central and Western Europe, and provide a review of the most prominent challenges to designing effective and efficient frequency control arrangements and the potential solutions discussed in the literature. Second, we provide a comprehensive update to previous literature on frequency control in the NEM (Riesz et al., 2015; Thorncraft et al., 2008; Thorncraft and Outhred, 2007). Our analysis benefits from recent experience in the NEM that encompasses deteriorating frequency performance, the reintroduction of mandatory requirements and integrating higher shares of VRE. While several of these aspects have been discussed independently in the literature, this paper seeks to provide a structured and holistic analysis of developments in the NEM and their implications for frequency control arrangement design. Third, this article advocates for designers placing a greater emphasis on delivering forward-looking frequency control arrangements during energy transition through the implementation of more robust regulatory mechanisms and ensuring that market-based mechanisms are capable of supporting FCS investment. As highlighted in the following sections, these design features have received surprisingly little attention in the literature.

The rest of the chapter is structured as follows. In Section 3.4, we provide an overview of typical frequency control arrangements, with a focus on restructured electricity industries in North America and Europe, and the main challenges faced in their design. We describe the NEM, its frequency control arrangements and the specific challenges posed by increasing penetrations of VRE and other IBR in Section 3. In Section [sec:insights], we analyse the performance of the NEM's frequency control arrangements in responding to the challenges explored in Section 2, with primary frequency response and regulation (secondary frequency response) services in the NEM as case studies. Based on our analysis, we conclude by offering four key insights to operators, regulators and marketbodies that include understanding control action interactions; ensuring that arrangements are capable of supporting investment in FCS capability; monitoring, assessing and remunerating FCS performance; and considering both regulatory and market-based mechanisms in the design of effective and efficient frequency control arrangements.

3.4 Context

3.4.1 Conventional frequency control schemes

SOs employ hierarchical and sequential frequency control schemes. In most power systems, such schemes implicitly include inertial response and explicitly define FCS such as primary frequency response (PFR), secondary frequency response (SFR) and tertiary frequency response (TFR). In general, once frequency has deviated from the system nominal value, synchronous machines provide an inertial response that is inherent and immediate in slowing the rate of change of frequency (RoCoF). Within seconds, generators and/or loads provide autonomous and decentralised control action through PFR (Eto et al., 2018; Machowski et al., 2020). PFR arrests the frequency deviation to enable the slower and more centralised control actions of SFR and TFR to return the power system frequency to its nominal value (Ela et al., 2012b; Eto et al., 2010). Should system frequency continue to rise or fall beyond the system's allowable limits, emergency protection schemes such as under-frequency load shedding (UFLS) and over-frequency generation shedding (OFGS) relays may be triggered. In some systems, RoCoF relays are also used to prevent high RoCoFs from tripping or damaging equipment and to contain frequency nadirs and zeniths (Akram et al., 2020; DGA Consulting, 2016; Miller et al., 2017a).

3.4.2 Procurement of frequency control services

Except for inertial response from synchronous machines, the SO procures FCS capacity from capable resources within its control area and, in the case of SFR and TFR, activates FCS energy if necessary. In electricity industries where the SO owns most if not all the generation assets (i.e. a vertically-integrated utility), the SO is able to jointly schedule generation and FCS capacity with knowledge of the condition of the system and the status and cost structures of their plant. However, many electricity industries have undergone some degree of restructuring, which has created a greater role for competitively-oriented decentralised decision-making (van der Veen and Hakvoort, 2016) . The diverse outcomes of restructuring processes and differences in technical characteristics (e.g. capabilities of resource mix and network topology) have led to a wide range of frequency control arrangements across power systems (Poplavskaya and de Vries, 2019; Y. Rebours et al., 2007) , which have been reviewed and compared extensively within industry and academic literature (Banshwar et al., 2018; Brooks and Lesieutre, 2019; Ela and Hytowitz, 2019; Hewicker et al., 2020; Lopez et al., 2020; Ocker et al., 2016; Y. G. Rebours et al., 2007a, 2007b; Reishus Consulting LLC, 2017; Zhou et al., 2016).

In restructured electricity industries, the provision of more passive FCS (e.g. ride-through capabilities) is usually mandated by regulatory mechanisms such as connection agreements and grid codes, whereas FCS that require additional response capabilities or impose opportunity-costs on suppliers are procured and remunerated by the SO through market-based mechanisms.

In Sections 3.4.3 & 3.4.4, we provide an overview of typical features[2] and key developments in market-based mechanisms for procuring FCS in North America and Central and Western Europe, respectively. These regions best represent the two prevailing short-term wholesale electricity market models: central dispatch markets, in which the SO issues dispatch instructions, and decentralised or self-dispatch markets, in which resource dispatch is managed by market participants (Ahlqvist et al., 2018). Given that FCS and energy are partially substitutable goods, the characteristics of short-term wholesale electricity markets heavily influence the design of FCS arrangements and thus these regions provide an interesting contrast. However, despite their differences, the SO plays a central role in both of these regions as they determine the area demand for FCS capacity, activate FCS energy as required and are ultimately responsible for ensuring that the power system is balanced and securely operated.

3.4.3 North American markets

In North America, central dispatch wholesale electricity markets are operated by an Independent System Operator (ISO) or Regional Transmission Organization (RTO) and are distributed across three synchronous areas. These markets consist of two short-term centralised platforms: a day-ahead market and a real-time market. In the day-ahead market, the SO solves a security-constrained unit commitment problem using supply offers (single or three-part) and demand bids (quantity or price-quantity) to produce day-ahead locational marginal prices and a financially-binding hourly schedule. In the real-time

[2]We note that there are numerous differences between jurisdictional arrangements and terminology in each of these regions. For a more general overview of potential procurement models, refer to Billimoria et al. (2020).

market, the SO solves a security-constrained economic dispatch problem (typically every five minutes) using generator price-quantity offers and a demand forecast to produce real-time locational marginal prices and a set of physically and financially binding dispatch instructions. Thus, each short-term market is cleared to maximise social welfare whilst respecting network and system security constraints (Chow et al., 2005; Cramton, 2017).

Except for Frequency Responsive Reserves (i.e. PFR), operating reserves (i.e. FCS capacity) are explicitly procured by placing an obligation on load-serving entities to self-provide or purchase their share from SO-run FCS markets (Ela et al., 2012b; Zhou et al., 2016). These FCS markets are usually integrated into day-ahead market and, in most jurisdictions, the real-time market. Standard products in North American markets include Regulation (i.e. SFR during normal operation), Spinning and Non-Spinning Reserves (i.e. TFR deployed following an event) (Ela and Hytowitz, 2019; Hewicker et al., 2020; Zhou et al., 2016). Participants can submit offers for FCS in addition to offer for energy. Unit commitment and economic dispatch permit co-optimisation of energy and FCS procurement. From the perspective of the SO, co-optimisation ensures that the total system cost of achieving an energy supply-demand balance is minimised alongside FCS requirements, subject to network and system security constraints. From the perspective of participants, co-optimisation leads to an FCS price that not only reflects the price offer of the marginal resource, but also any "profit" it forgoes in the energy market (assuming supplier offers reflect their short-run marginal costs) (Ela et al., 2012a; Isemonger, 2009). As such, ISO/RTO FCS markets can compensate opportunity-costs related to the day-ahead and/or real-time market but only allocate costs to load-serving entities through a procurement obligation.

Though North American FCS markets have predominantly procured and remunerated FCS capacity, ISO/RTOs (except Texas' ISO, ERCOT) were ordered to also remunerate Regulation providers for the quantity of energy provided whilst accurately following control signals by the Federal Energy Regulatory Commission's (FERC) Order 755 (Commission, 2011). As such, Regulation providers offer a quantity of capacity, a price for capacity and a price for "mileage", which is the energy delivered. Remuneration for Regulation takes performance (the ability of a resource to follow the ISO/RTO's control signals) into account, though how this is implemented varies between ISO/RTOs (Ela and Hytowitz, 2019; Fernández-Muñoz et al., 2020). A notable example is the PJM RTO, which uses both a standard SFR control signal (RegA) and faster SFR control signal (RegD) intended for battery energy storage systems (BESS). PJM determines how interchangeable a resource's RegD provision is with RegA provision (the marginal benefit factor) to clear the Regulation market and calculates a performance score for use in market clearing and settlement. However, according to the independent market monitor, the omission of the marginal benefit factor from market settlement has led to perverse market outcomes (Brooks and Lesieutre, 2019; Monitoring Analytics, 2021).

3.4.4 European markets

Most of the electricity markets of Central and Western Europe are self-dispatch and consist of two short-term platforms: the day-ahead market and the intraday market, which can be continuous, composed of frequently-run discrete auctions or a combination of the two. Each of these platforms is coupled across the majority of market zones in Europe, with a single price coupling algorithm used to simultaneously clear zonal day-ahead markets and a single order book compiled to match cross-zonal intraday orders (EPEX Spot, n.d.; NEMO Committee, n.d.). In contrast to North American electricity markets, the market operator is responsible for market operation and is distinct from the Transmission System Operator (TSO). Generation and load are managed by Balancing Responsible Parties (BRP), which must submit binding operational schedules to the TSO ahead of delivery (often by the day prior to delivery). As BRPs become aware of potential deviations closer to real time (e.g. improved forecasts), they are able to adjust their submitted schedules (i.e. remain "balanced") through trades on the intraday market (Lago et al., 2021; Müsgens et al., 2014). BRPs face financial repercussions if they are imbalanced via an imbalance price and, in some jurisdictions, are legally obliged to be balanced (ENTSO-E WGAS, 2021).

Following gate-closure of the intraday market, residual imbalances are primarily addressed by FCS (known as balancing services) procured by the TSO. Standard FCS in Europe include Frequency Containment Reserve (i.e. PFR), automatic Frequency Restoration Reserves (i.e. SFR), and manual Frequency Restoration Reserves and Replacement Reserves (i.e. both TFR), with minimum technical requirements for each specified by the European Network of Transmission System Operators for Electricity (ENTSO-E) (European Network of Transmission System Operators for Electricity, 2013). Depending on the FCS product and the jurisdiction, TSOs may distinguish between FCS capacity (balancing capacity) and the delivery of FCS energy (balancing energy). The provision of one or both is mandated in some cases, but where both are procured competitively, Balancing Service Providers (BSP) typically submit separate offers for FCS capacity and FCS energy (Abbasy, 2012). FCS capacity markets are often cleared days to months in advance of real-time whereas the FCS energy market, which effectively constitutes merit-order or pro rata activation of capacity for FCS energy provision, is cleared within an hour or minutes of real-time (ENTSO-E WGAS, 2021; Ocker et al., 2016; Poplavskaya and de Vries, 2019). FCS capacity costs are typically allocated to power system users via a grid tariff. FCS energy costs are typically allocated to BRPs based on their schedule deviations and an imbalance price, which may differ from the FCS energy price paid to BSPs (Hirth and Ziegenhagen, 2015; Vandezande et al., 2010). As such, European FCS markets generally disincentivise causers of imbalance through the imbalance price, which may also recover or reflect the cost of FCS energy. However, since FCS capacity markets are typically decoupled from and cleared ahead of short-term energy markets, perceived opportunity-costs based on expected short-term energy market prices must be internalised within participants' FCS offers.

Given the relatively high degree of interconnection between transmission systems in Central and Western Europe, cross-TSO initiatives are in place and being expanded to address imbalances and share FCS across the Continental Europe synchronous area. When sufficient cross-TSO transmission capacity is available, initiatives currently in place enable participating TSOs to jointly procure Frequency Containment Reserve capacity, net imbalances (i.e. reduce the demand for SFR by aggregating individual control area imbalances) and jointly procure automatic Frequency Restoration Reserve capacity and energy (European Network of Transmission System Operators for Electricity, 2020). Further efficiency gains are expected following the implementation of integrated market platforms for imbalance netting and balancing energy for SFR and TFR. The implementation of these platforms is mandated by the European Commission's European Balancing Guideline and requires certain FCS product definitions and market features to be harmonised across the balancing energy markets of participating

TSOs (50hz, 2017; European Commission, 2017).

3.5 Designing frequency control arrangements

As with any policy problem, designing frequency control arrangements in restructured electricity industries requires design principles, variables and performance criteria to be established. The public good characteristics of frequency control have heavily influenced arrangement design principles across jurisdictions, such as the common preference for the SO to centrally coordinate FCS procurement and activation (Müsgens et al., 2014; Y. Rebours et al., 2007). In contrast, though some design variables are common, others may only apply to particular systems based on their resource mix, network topology and/or market design. Y. Rebours et al. (2007) discuss design variables for central dispatch markets related to the following arrangement features:

1. FCS procurement;
2. Price formation, which when efficient should lead to FCS prices not only reflecting the true cost of the service, but also its true value to the system; and
3. Allocation of the cost of FCS.

Similarly, Abbasy (2012) discusses the main design variables applicable to European self-dispatch markets. van der Veen and Hakvoort (2016) build upon this work to provide a more comprehensive treatment of design variables in self-dispatch markets. Y. Rebours et al. (2007), Abbasy (2012) and van der Veen and Hakvoort (2016) all propose some variation of effectiveness and efficiency as performance criteria, with van der Veen and Hakvoort (2016) analysing the various trade-offs between and within each criterion.

Despite the well-defined nature of the design problem, there are several challenges to achieving effective and efficient arrangements. In Sections 3.5.1 and 3.5.2, we present the most prominent challenges and their treatment in the literature.

3.5.1 The influx of VRE and other IBR in power systems

As discussed in Section 3.3, VRE adds variability and uncertainty to power systems which, at the very least, can lead to increased procurement and activation requirements for PFR and SFR during normal operating conditions (Ela et al., 2011). Three proposals to address this issue and thus reduce FCS requirements with growing penetrations of VRE have been discussed in the literature. The first is to shorten energy market trading/dispatch intervals (Ocker and Ehrhart, 2017; Riesz and Milligan, 2015) and the time between market gate closure and dispatch (Katz et al., 2019), thereby enabling scheduling based on up-to-date system conditions and forecasts. The second is to increase coordination between control areas within a synchronous area by netting imbalances (King et al., 2011), jointly procuring and dispatching FCS (Scherer et al., 2013) or aggregating them into a single market region (Milligan and Kirby, 2010; Riesz and Milligan, 2015). These two proposals alone have delivered significant system savings in Germany despite growing penetrations of VRE (Hirth and Ziegenhagen, 2015; Ocker and Ehrhart, 2017). The third is for the SO to determine the required quantity of FCS capacity (*dimensioning*) using dynamic and probabilistic approaches (as opposed to static and deterministic) that adequately reflect current or expected power system conditions and an acceptable level of risk, such as a reliability standard (De Vos et al., 2019; Holttinen et al., 2013; Ortega-Vazquez et al., 2020).

In recent years, SOs have become increasingly concerned with growing penetrations of asynchronous IBR leading to higher RoCoFs and fewer resources offering conventional FCS (Denholm et al., 2020; DGA Consulting, 2016; Hartmann et al., 2019). However, VRE and other IBR are able to provide tunable conventional FCS, FFR and/or an inherent response that strongly resembles the inertial response of synchronous machines[3] if this is facilitated by arrangement design (Fernández-Muñoz et al., 2020; Mancarella and Billimoria, 2021; Miller et al., 2017b). Following a contingency event in a low-inertia power system, rapid FCS from IBR can mitigate higher RoCoFs, which when unabated can lead to deeper frequency nadirs and zeniths and the subsequent activation of UFLS or OFGS (Australian Energy Market Operator, 2017; NERC Inverter-Based Resource Performance Task Force, 2020; Tielens and Van Hertem, 2016).

3.5.2 Achieving economic efficiency

Achieving short-run efficiency entails supplier costs being reflected in their offers and adequately propagated to FCS prices, and the SO assigning at least some portion of FCS costs to system users that create a need for procure-

[3]The terms *virtual, emulated and synthetic* inertia have been used in the literature to refer to a proportional active power response to RoCoF. However, these terms do not distinguish whether the inverter control scheme provides an inherent response (i.e. from inverters operated as a voltage source which are commonly referred to as *grid-forming inverters* (Cherevatskiy et al., 2020; Lin et al., 2020)) or a controlled response following frequency measurement (Eriksson et al., 2018; Tielens and Van Hertem, 2016).

ment or activation. A widely used pricing approach in ISO/RTO co-optimised FCS markets is a marginal price which incorporates the marginal resource's short-term market opportunity-costs and their offer, which could reflect potential mileage or wear-and-tear costs (Frew et al., 2021; Zhou et al., 2016). Though improving cost-allocation has been repeatedly proposed in North American literature (Ela et al., 2012a; Isemonger, 2009; Milligan et al., 2011), FCS costs are predominantly socialised across loads based on demand or consumption. In Europe, however, much attention has been given to FCS market pricing, scoring (the order in which offers are selected) and cost-allocation. Specifically, literature on European FCS markets has explored whether pay-as-bid or uniform pricing better facilitates suppliers revealing their true costs (Hirth and Ziegenhagen, 2015; Müsgens et al., 2014; Ocker et al., 2018), the particular offers scoring should consider (Ehrhart and Ocker, 2021; Müsgens et al., 2014) and the design of imbalance prices to sufficiently incentivise short-term balancing (Hirth and Ziegenhagen, 2015; Papavasiliou, 2020; Vandezande et al., 2010). Regardless, both European and North American literature suggest that increased competition in FCS markets is a priority. This could be facilitated by enabling distributed and utility-scale VRE and IBR to qualify for FCS provision, reducing minimum offer quantities, separating raise and lower (positive and negative) products and increasing market clearing frequency and the time resolution of FCS products (Frew et al., 2021; Hirth and Ziegenhagen, 2015; Lago et al., 2021; Poplavskaya and de Vries, 2019). Despite the typically "shallow" nature of FCS markets (i.e. additional supply can significantly reduce prices (Riesz and Milligan, 2015)), dynamic efficiency has received considerably less attention. Notable exceptions include Papavasiliou (2020) and Frew et al. (2021), who briefly discuss the potential for FCS scarcity pricing to better reflect the true value of system reliability and support investment in FCS.

An additional challenge in implementing efficient FCS markets involves the trade-offs that must be considered. As outlined in Section 3.3, some mechanisms that improve efficiency may come at the expense of visibility, control and redundancy afforded to the SO, which typically does not own any FCS-capable assets. The former is typically achieved using market-based mechanisms and the latter through regulatory mechanisms. Ela et al. (2012b), Billimoria et al. (2020), Mancarella and Billimoria (2021) and Lal et al. (2021) discuss several prerequisites for implementing market-based mechanisms and stress that balance between market-based and regulatory mechanisms may be required. However, achieving this balance can be challenging due to the asymmetry between the risk of an event and its consequences, and that between the benefits of market efficiency and the cost of resilient and robust mitigation measures (Lal et al., 2021; Mancarella and Billimoria, 2021). Another trade-off is the arbitrary definition of FCS products. Market-based mechanisms will work best when FCS are ”discrete” commodities and fungible. However, this ignores the wide “spectrum” of resource technical capabilities. Favouring fungibility may obscure physical and control interdependencies between FCS and restrict or fail to incentivise higher quality provision, thereby leading to an inefficient overall outcome (Gimon, 2020; MacGill and Esplin, 2020).

Chapter 4

Research containing a figure

4.1 Introduction

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4.2 Method

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4.2.1 Subsection 1

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4.2.2 Subsection 2

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4.3 Results

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4.4 Discussion

Figure 4.1 shows how to add a figure. Donec ut lacinia nibh. Nam tincidunt augue et tristique cursus. Vestibulum sagittis odio nisl, a malesuada turpis blandit quis. Cras ultrices metus tempor laoreet sodales. Nam molestie ipsum ac imperdiet laoreet. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas.

Figure 4.1: RV Calypso is a former British Royal Navy minesweeper converted into a research vessel for the oceanographic researcher Jacques-Yves Cousteau. It was equipped with a mobile laboratory for underwater field research.

4.5 Conclusion

This is the conclusion to the chapter. Quisque nec purus a quam consectetur volutpat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. In lorem justo, convallis quis lacinia eget, laoreet eu metus. Fusce blandit tellus tellus. Curabitur nec cursus odio. Quisque tristique eros nulla, vitae finibus lorem aliquam quis. Interdum et malesuada fames ac ante ipsum primis in faucibus.

Figure 4.2: This is not a boat

Chapter 5

Research containing a table

5.1 Introduction

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5.2 Method

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5.2.1 Subsection 1

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5.2.2 Subsection 2

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5.3 Results

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Table 5.1: Important data for various land masses.

Landmass	% stuff	Number of Owls	Dolphins per Capita	How Many Foos	How Many Bars	Forbidden Float
North America	94%	20,028	17,465	12,084	20,659	1.71
Central America	91%	6564	6350	8,189	12,012	1.52
South America	86%	3902	4127	5,205	6,565	1.28
Africa	84%	2892	3175	3,862	4,248	1.1
Europe	92%	20,964	17,465	15,303	24,203	1.58
Asia	87%	6852	6350	8,255	11,688	1.47
Oceania	87%	4044	4127	5,540	6,972	1.28
Antarctica	83%	2964	3175	4,402	4,941	1.13

5.4 Discussion

This is the discussion. As we saw in Table Table 5.1, many things are true, and other things are not. Etiam sit amet mi eros. Donec vel nisi sed purus gravida fermentum at quis odio. Vestibulum quis nisl sit amet justo maximus molestie. Maecenas vitae arcu erat. Nulla facilisi. Nam pretium mauris eu enim porttitor, a mattis velit dictum. Nulla sit amet ligula non mauris volutpat fermentum quis vitae sapien.

5.5 Conclusion

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Chapter 6

Final research study

6.1 Introduction

This is the introduction. Nunc lorem odio, laoreet eu turpis at, condimentum sagittis diam. Phasellus metus ligula, auctor ac nunc vel, molestie mattis libero. Praesent id posuere ex, vel efficitur nibh. Quisque vestibulum accumsan lacus vitae mattis.

6.2 Method

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6.2.1 Subsection 1

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6.2.2 Subsection 2

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6.3 Results

These are the results. Curabitur vulputate nisl non ante tincidunt tempor. Aenean porta nisi quam, sed ornare urna congue sed. Curabitur in sapien justo. Quisque pulvinar ullamcorper metus, eu varius mauris pellentesque et. In hac habitasse platea dictumst. Pellentesque nec porttitor libero. Duis et magna a massa lacinia cursus.

6.4 Discussion

This is the discussion. Curabitur gravida nisl id gravida congue. Duis est nisi, sagittis eget accumsan ullamcorper, semper quis turpis. Mauris ultricies diam metus, sollicitudin ultricies turpis lobortis vitae. Ut egestas vehicula enim, porta molestie neque consectetur placerat. Integer iaculis sapien dolor, non porta nibh condimentum ut.

6.5 Conclusion

This is the conclusion to the chapter. Nulla sed condimentum lectus. Duis sed tempor erat, at cursus lacus. Nam vitae tempus arcu, id vestibulum sapien. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus.

Chapter 7

Conclusion

7.1 Thesis summary

In summary, pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Nunc eleifend, ex a luctus porttitor, felis ex suscipit tellus, ut sollicitudin sapien purus in libero. Nulla blandit eget urna vel tempus. Praesent fringilla dui sapien, sit amet egestas leo sollicitudin at.

7.2 Future work

There are several potential directions for extending this thesis. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Aliquam gravida ipsum at tempor tincidunt. Aliquam ligula nisl, blandit et dui eu, eleifend tempus nibh. Nullam eleifend sapien eget ante hendrerit commodo. Pellentesque pharetra erat sit amet dapibus scelerisque.

Vestibulum suscipit tellus risus, faucibus vulputate orci lobortis eget. Nunc varius sem nisi. Nunc tempor magna sapien, euismod blandit elit pharetra sed. In dapibus magna convallis lectus sodales, a consequat sem euismod. Curabitur in interdum purus. Integer ultrices laoreet aliquet. Nulla vel dapibus urna. Nunc efficitur erat ac nisi auctor sodales.

Appendix 1: Some extra stuff

Add appendix 1 here. Vivamus hendrerit rhoncus interdum. Sed ullamcorper et augue at porta. Suspendisse facilisis imperdiet urna, eu pellentesque purus suscipit in. Integer dignissim mattis ex aliquam blandit. Curabitur lobortis quam varius turpis ultrices egestas.

Appendix 2: Some more extra stuff

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