JAMES COOK UNIVERSITY

COLLEGE OF SCIENCE & ENGINEERING

EG4012

Electronic Systems and Internet of Things Engineering

Application of Synchronous Condensers in Conventional Diesel Generators

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Thesis submitted to the School of Engineering & Physical Sciences in partial fulfilment of the requirements for the degree of

Bachelor of Engineering with Honours

(Electronic Systems and Internet of Things Engineering)

06/10/2023

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Abstract

This study offers a detailed examination of the integration of synchronous condensers (SCs) and SSS (Synchro-Self-Shifting) clutches into conventional diesel generators (DGs). Through a series of simulations and comparative analyses, the research investigates the performance and feasibility of these alternative technologies in scenarios characterized by load switching, three-phase faults, and instantaneous clutch engagement and disengagement.

In the context of load switching conditions, SCs demonstrate promising results, showcasing resilience in terms of Rate of Change of Frequency (ROCOF) compliance and voltage correction. Despite slightly slower response times compared to DGs, SCs help to maintain regulatory standards while absorbing minimal power from the grid, offering a sustainable solution for modern isolated electricity grids.

When considering the fault condition analyses, distinct advantages and disadvantages for each technology are discovered. Under three-phase fault scenarios, DGs exhibit faster recovery to steady-state operation but suffer from significant frequency fluctuations, potentially exceeding permissible ROCOF limits. However, this is an element on diesel engine governor tuning which can be modified to suit. In contrast, SCs provide more stable grid frequency responses, although they have longer recovery times. Both technologies, however, excel in supplying necessary fault current for current protection system requirements that are designed for a synchronous machine dominated grid.

The study also investigates the effects of SSS clutch engagement and disengagement, revealing the intricate dynamics involved. Instantaneous clutch engagement poses substantial challenges to both the generator and engine, requiring careful control mechanisms to ensure grid stability. Conversely, clutch disengagement prompts concerns about grid frequency stability, excitation system response, and rotor speed regulation.

In summary, this research offers valuable insights into the integration of an SSS clutch into a DG and a comparison between SCs and DGs in high DER penetration grids. The findings underscore the need for tailored solutions and meticulous engineering considerations to achieve grid resilience and sustainability, thereby facilitating informed decisions for power system engineers and planners. Further research in control mechanisms and clutch operation is recommended to optimize these technologies for real-world applications.

Acknowledgements

I would like to express my heartfelt gratitude to all those who have contributed to the realization of this project. Your support, guidance, and encouragement have been instrumental in making this endeavour a reality.

First and foremost, I want to thank my family for their unwavering support and understanding throughout this journey. Your love and patience have been my anchor during the ups and downs of this project and degree.

I extend my sincere appreciation to my supervisors, Yang Du and Alan Louis, for their invaluable mentorship, expertise, and unwavering belief in my abilities. Your guidance has been instrumental in shaping my research and academic growth.

I am deeply thankful to my colleagues and friends who provided valuable insights, constructive feedback, and moral support during this project. Your camaraderie made the journey enjoyable and meaningful.

My gratitude extends to a research participant Grahame Lendon who willingly shared his time and knowledge, without whom this study would not have been possible.

I am indebted to the staff at James Cook University, especially those in the Engineering Department for their assistance and resources that facilitated the research process.

Lastly, I want to express my appreciation for the countless authors, scholars, and experts whose work served as a foundation for my research. Their contributions have paved the way for meaningful advancements in this field.

To all those mentioned and countless others who have played a part, I am deeply thankful for your support and contributions. This project would not have been possible without each and every one of you.

With sincere gratitude,

Ashley Mauro

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List of Acronyms

SC – Synchronous Condenser

SM – Synchronous Machine

DG – Diesel Generator

DER – Distributed energy resource

ROCOF – Rate of Change of Frequency

SSS – Synchro-Self-Shifting

PV – Photovoltaic

BESS – Battery Energy Storage System

IBG – Inverter-based generators

OC – Overcurrent Relays

CB -Circuit Breaker

AVR - Automatic Voltage Regulator

WD – Wind-Diesel

WO – Wind-only

1. Introduction

Although synchronous condensers (SCs) are considered old technology, their potential application in modern electricity systems has recently come to light. SCs are considered a key enabler to distributed energy resources (DER) penetration and a low carbon future and are vital for power system security in low synchronous machine power systems. A SC is described as a synchronous machine designed to operate with no mechanical load (the rotor is free to rotate without any constraints due to load or prime movers) and can produce or consume reactive power depending on the magnitude of the excitation current [1]. In addition, SC's can contribute short circuit current and system inertia to trip protection schemes and reduce the rate of change of frequency (ROCOF) during system events via its stored kinetic energy.

There is a need to better understand the effects of the integration of a SC retrofitted diesel generator on the overall performance and stability of these systems. A diesel generator with the implementation of a Synchro-Self-Shifting (SSS) clutch, which automatically engages and disengages through shaft speed control only, could regulate the flow of power from the diesel engine to the synchronous machine *(Figure 1)*. This can be used to enhance the performance of microgrid systems in several ways.

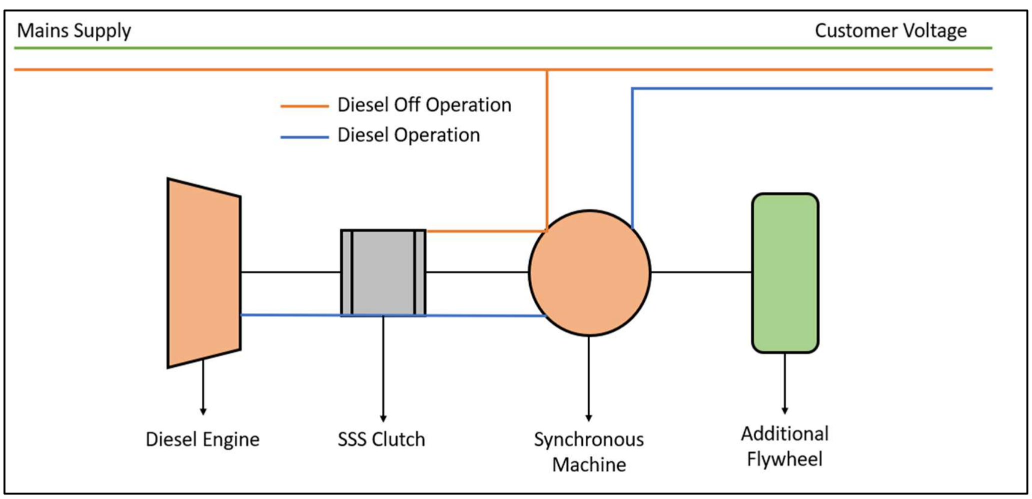

Figure 1: Application of Synchronous Condenser in Diesel Generator with the use of SSS Clutch.

Microgrids are classified as an electricity distribution system containing loads and distributed energy resources (DER) that can operate in a safe and controlled manner when either connected to or islanded from the main utility grid [2]. Many kinds of energy resources such as renewable energy sources (photovoltaic modules (PV) and wind turbines), diesel generators, and battery energy storage systems (BESS) make up the DERs that are used to provide reliable and safe power to the microgrid loads. As a result of these DERs, a microgrid can improve the efficiency of the grid and potentially resolve energy crisis across the world by supplying quality and reliable power to customers while reducing carbon footprint.

Moreover, isolated power systems are smaller utility grids that are usually isolated from the main utility grid that usually depend primarily on fossil fuels for power generation through diesel generators [3]. The increasing concern about the environmental impacts fossil fuels have on the environment in addition to the increasing costs of fossil fuels, and transport costs to remote and isolated sites, has accelerated the integration of renewable energy resources into these types of systems [4].

The utilisation of renewable energy has significantly increased over the last decade throughout the world. International pressure for decarbonisation of power sectors across the world is driving the high interest in renewable energy, and the deployment of renewable energy sources is a major lever in trying to achieve a net zero decarbonisation [5].

2. Literature Review

2.1. Challenges for Renewable Energy Integration into Power Systems

Renewable energy is defined by marketable energy that is produced by converting natural energy resources into useful energy forms [6]. These renewable technologies inherit the sunlight and its direct impact on the Earth's other natural sources (photons, wind, heating effects, falling water), and gravitational forces (the tides) as the resources for which they convert into useful energy forms [6]. Wave, wind, direct solar, and hydro are just a few of the renewable technologies that offer energy conversion today [7].

Accompanying the upside of renewable energy sources are some inherent problems with the integration of renewables into a utility microgrid. Power system inertia of a microgrid reduces due to the implementation of renewable energy, which decreases the ability to maintain energy balance and grid stability [2, 8].

In weak isolated networks, a large displacement of conventional diesel power generation can cause a reduction in power system safety, stability, and reliability [4]. Increased flexibility in power systems provides the grid with the ability to balance supply-demand, while also maintaining continuity in unexpected fault situations within the grid. The combination of high integration of renewable energy resources and a reduction in conventional synchronous generation inherently reduces the inertia within the microgrid and can result in a reduction of system reliability and flexibility [9, 10].

Such low inertia grids could potentially be at risk of experiencing an excessive rate of change of frequency (ROCOF) after a system fault [11]. ROCOF is described as the time derivative of the power system frequency and is an important characteristic that qualifies as the robustness of an electrical grid. An elevated ROCOF could potentially initiate tripping of other synchronous machines in the power systems and as a result, network frequency response may become vulnerable [11].

In addition to ROCOF, voltage instability is also an inherent issue with the increased integration of renewable energy. Voltage instability is initially a local characteristic that starts with an imbalance of reactive power in the grid, often caused by sudden changes in loads or load flow [12]. Since inverter-based generators (IBG) have significant differences compared to synchronous machines regarding reactive power contribution, the impacts they have on system dynamics are also much different to traditional synchronous generation. Hence, renewable energies limited ability to provide or absorb reactive power can result in voltage instability in the utility grid.

Distributed power systems are protected with the help of multiple current sensing devices such as overcurrent relays (OC), reclosers, and fuses. These devices monitor the current flow through the protection element and produce trip signals to the circuit breaker (CB) if the fault current flow is greater than the specified value. The current protection systems are well established for power systems which have conventional synchronous machines as their main fault current source.

Fault level is one of the key aspects of any power system that should be continuously monitored and has been used as a measure to reflect the strength of the system [13]. Usually, the higher the fault level the shorter electrical distance there is between the fault and generation point which is a sign of a stronger system. A fault level shortfall due to higher integration of DERs would negatively impact the system strength [13]. Most current protection schemes implemented are designed at the planning stage, however the large penetration of DERs may result in nuisance tripping of over current relays at distribution feeders which also may reach the distance relays of the transmission system [14].

The integration of renewables in the power system changes the fault current level and infeed is intermittent in nature [14], which could result in utility companies having to alter current protection systems. The fault level contribution of inverter based photovoltaic (PV) renewables has a range of 1 to 1.2 times the rated current, whereas in comparison the fault level from a synchronous based renewable system is in the range of 5 to 6 times its rated current [14, 15]. In this occurrence, the existing over current relays implemented in the planning stage fail to detect the weaker fault current from the DERs resulting in no operation of the relay [14], suggesting that the implementation of a synchronous machines is crucial to system security and reliability.

2.2. Synchronous Condenser

A Synchronous Condenser (SC) is described as a synchronous machine that is designed to operate at no mechanical load (the rotor is free to rotate without any constraints due to load or prime movers). Additionally, an SC can be a purpose-built machine or an existing generator that has either been converted to perform the functions of an SC as well as generate active power as required [16].

An SC can provide several capabilities to the electricity grid such as:

- Produce or consume reactive power depending on the value of the excitation current [1].
- Provides system inertia to reduce the rate of change of frequency (ROCOF) during system events via its stored kinetic energy [17].
- Provides fault current contribution during system faults to trip protection systems [18].

Furthermore, because an SC is a rotating machine, they do not have any voltage distortion and are synchronised directly to the grid. Until the 1940's, rotating SCs were used to supply reactive power and were normally located in utility substations, connected to the distribution voltage bus. SCs are dynamic sources which means their output can change quickly to balance reactive power need within the system [19].

By regulating the reactive power, SCs help maintain stable voltage and frequency in the grid, which is essential for ensuring the safe and efficient operation of the power system. Troubles can arise in the network in case of faults due to the reduced network inertia when there is no synchronous machines in service [20]. SCs are established technology which can be purchased for a specific task or retrofitted by talking advantage of decommissioned power plants, saving on implementation costs.

2.2.1. Application of Synchronous Condenser in Renewable Energy Networks

In renewable energy networks, SCs are often used to compensate for the variability of renewable energy sources, such as wind and solar power, which can cause fluctuations in the grid's voltage and frequency. When renewable energy sources are connected to the grid, their output can vary depending on the weather and other factors, leading to changes in voltage and frequency that can affect the stability of the power system [20]. This is usually accompanied by the reduction of synchronous machines present in the power system. SCs can help address this issue by providing reactive power that can stabilise the grid and improve the reliability of the renewable energy network.

There are numerous studies that support the argument of SCs application in renewable energy rich electricity grids to help with frequency stability. Arayamparambil Vinaya Mohanan et al. [18] conducted a study whereby adding a synchronous condenser to a utility grid that had a synchronous generator (SG) and photovoltaic (PV) present, and concluded that the addition of an SC enhanced the maximum level of PV integration from 18% to around 64%. In addition, Arayamparambil Vinaya Mohanan et al. [18] also stated that the inherent inertia an SC provides, is instantaneous energy to the system which does not involve any control or communication delays; the energy had a positive effect on the frequency stability improving the ROCOF by 38%. Furthermore, Ha Thi et al. and Hansen et al. [8, 21] also stated that an SC is an advantageous solution for frequency and voltage stability for low inertia islanded power grids during grid perturbations.

In addition to frequency stability, Arayamparambil Vinaya Mohanan et al. [18] again concluded the integration of an SC in a low inertia grid improved voltage stability by controlling the reactive power in the network. The bus voltage deviation during transients was reduced by 80% in their presented case, proving that the SC actively participates in reactive power compensation.

In the context of fault currents, an SC can be used to help the delivery of fault currents that occur in an electrical power system. In a study conducted by Matthews et al. [22], they concluded that an SC is a viable solution for delivering fault current in inverter-based systems. Further stating that SCs can also help with fault location within the grid due to an inverters inherent ability to limit its own current output through internal protection, enabling traditional alternating current (ac) protection systems to be utilised.

Overall, SCs are an important technology for integrating renewable energy sources into power systems. By providing reliable voltage and frequency control, they can help ensure that renewable energy networks are stable and efficient, while also reducing the need for conventional power plants that rely on fossil fuels.

2.2.2. Comparison of SC to other technology

A comparison between studies regarding SCs and other forms of technology that provide the same abilities was needed. Regarding voltage recovery during faults due to reactive power compensation, another form of technology is a power electronic called static-var compensator

(SVC). In a study conducted by Urdal et al. [23], the application of an SVC in the HV connections between England and Scotland, stability can be achieved with the application of an SVC in a non-synchronous generation (NSG) grid. However, the study does not evaluate the optimal ratings of an SVC for adequate applications [24]. In addition, Mahmud et al. [24] also stated that a SC outperforms an SVC in both technical and economic aspects. Concluding that an SC prevails as a better solution than an SVC for providing system strength in high wind penetration networks.

Regarding fault current contribution, Matthews et al. [22] concluded that in both supercapacitor and SC compensation methods, sufficient current was provided to remove the remote fault in the grid. Hence, both schemes allowing traditional ac protection systems to be used. Furthermore, Matthews et al. [22] also stated that the fault clearance times were relatively close for the drastically differing dynamic solutions. Further stating that the choice between the two technologies came to the supercapacitor's waveforms being more stable through the fault, or the low cost of an SC implementation into the grid.

Finally Prevost et al. [25] conducted a study comparing the cost for stability of a system for both a Grid Forming Inverter (GFI) and a SC stating that both technologies are good candidates as their estimated cost are relatively equal. However further stating that it can be assumed that the cost of GFIs will decrease whereas the cost of SCs is mature and stable. Conversely, this price could be mitigated if existing synchronous machine get transformed into SCs [26]. Lastly, Prevost et al. [25] stated that a comparison between GFIs and SCs under fault conditions needs to be further analysed.

Below is a table comparing various technologies and what they provide to a utility grid.

	Synchronous Generator	**Synchronous Condenser**	**Inverter-Based Generation (Grid-FORMING)**
Fault Level Contribution	✓	✓	✗
Provides Inertia	✓	✓ (Depends on flywheel inertia)	✓ (Using virtual synchronous)
Voltage Control	✓	✓	✓
Frequency Control	✓	✓	✓
Provides Continuous Energy	✓	✗	✓

Table 1: Comparison of technologies

2.2.3. Synchronous Condenser Models in Simulink

Simulink is a powerful simulation tool that can be used to model and simulate the behaviour of a SC. The Specialized Power Systems library in Simulink provides several blocks that can be used to create a SC model.

To create a SC model in Simulink, various machine parameters such as rated voltage, rated power factor, and synchronous reactance need to be defined. Initial conditions also need to be set for the machine, such as the initial rotor angle, speed, and voltage. Once the parameters and initial conditions are set, the SC model can be connected to the rest of the model, including the power system and control system.

The work conducted by Igbinovia et al. [27] resulted in a Simulink model being used to investigate the effects the application of a SC can have on a low inertia grid. In addition, Igbinovia et al. [27] created various Simulink models for the application of a SC at various points in the power system scheme.

Moreover, Igbinovia et al. [28] also used Simulink to model the application of a SC in a 33KV MV electricity network for cost implication analysis *(App.1)*. Furthermore, Nguyen et al. [29] also utilized Simulink to simulate how the effect a SC can have on voltage and frequency support in a Microgrid *(App. 2)*.

2.3. Synchro-Self-Shifting (SSS) Clutch

A Synchro-Self-Shifting (SSS) clutch is a type of clutch commonly used in power systems to engage or disengage rotating equipment, such as generators or motors *(Figure 2)*. It is designed to operate at synchronous speed, which refers to the speed at which the rotating equipment is designed to operate. An SSS clutch is a long-term component of the propulsion systems used in US Navy vessels [30].

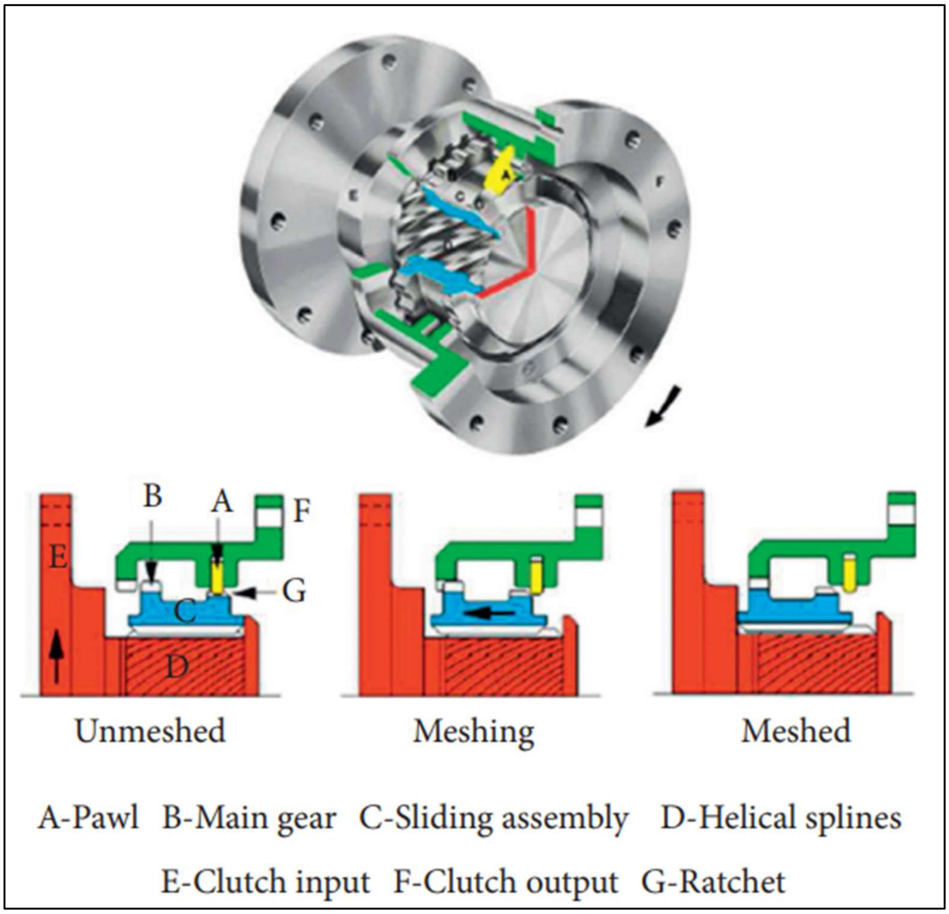

Figure 2: Meshing process of an SSS clutch [31].

The SSS clutch consists of two parts: a driving component and a driven component. The driving component is usually connected to a source of power, such as a diesel engine or gas turbine. The driven component is connected to the rotating equipment, such as an alternator. When the clutch is engaged, the driving component and the driven component are locked together and rotate at the same speed [32]. When the clutch is disengaged, the driving component and the driven component are separated, and the rotating equipment is free to spin independently from the source of power.

The unique feature of the SSS clutch is that it is designed to automatically shift from the engaged to the disengaged position and vice versa [33]. The engagement of the SSS clutch teeth is purely accomplished automatically by shaft speed without any external control or communication, eliminating the possibility of error [34].

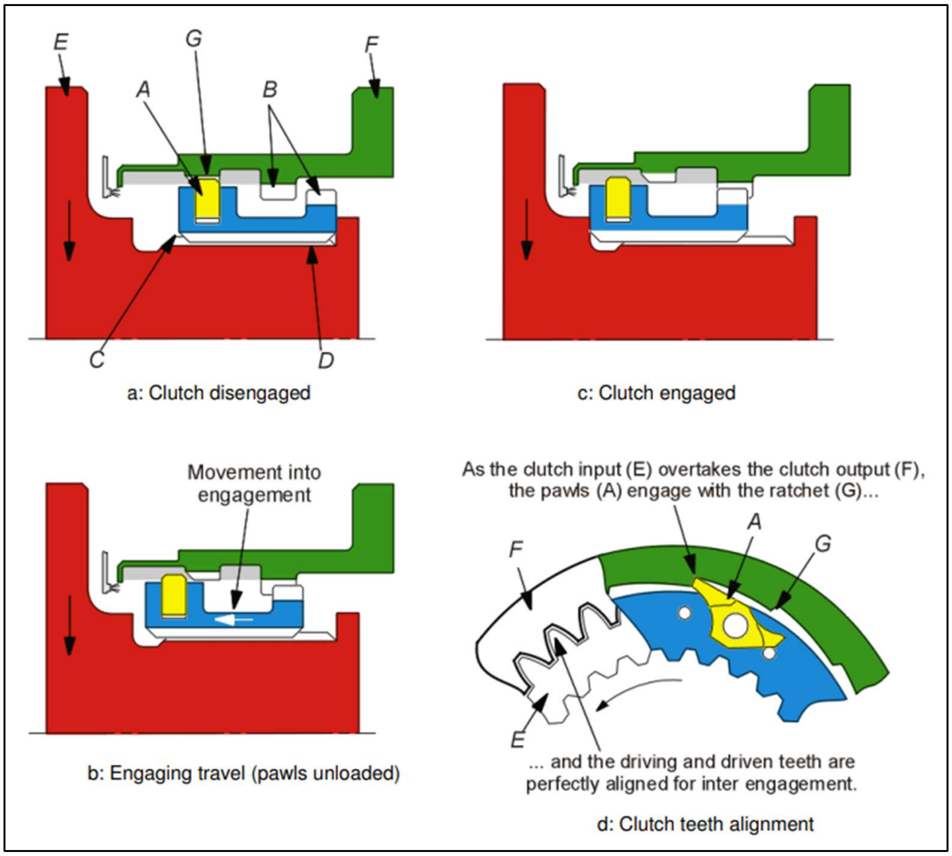

Figure 3: Detailed graphic of SSS clutch engagement process [32].

The input shaft (E) has helical splines (D) and on the helical splines is a sliding component (C). In *Figure 3(a)* the sliding component has clutch teeth (B) at one end and a set of ratchet teeth (G) at the other end. When the input shaft rotates the sliding element rotates with the input element until a ratchet tooth (G) contacts the tip of the pawl (A) to prevent rotation of the sliding component comparative to the output clutch ring (F) (*Figure 3(d))* [32].

As the input shaft continues to spin, the sliding component moves axially along the helical splines of the input shaft. When a ratchet tooth is in contact with the pawl tip, the clutch engaging teeth are perfectly aligned for engagement, and will pass smoothly into mesh in a straight-line path. As the sliding component transitions along the input shaft, the pawl passes out of contact with the ratchet tooth, allowing the clutch teeth to come into edge contact and maintain the engaging travel as shown in *Figure 3(b)* [32].

The only load on the pawl is that necessary to shift the reasonably lightweight sliding component along the helical splines. Driving torque from the input shaft will only be transmitted through the clutch teeth (B) when the sliding component concludes its axial travel by contacting an end stop on the input shaft, with the clutch teeth fully engaged and with the pawls out of contact with the ratchet teeth, thus unloaded *(Figure 3(c))* [32].

Like a screw connection, when a nut is screwed against the head of a bolt, no external thrust is produced. Similarly, when the sliding component of an SSS Clutch contacts its end stops and the clutch transmits driving torque, no external thrust loads are produced by the helical splines. If the speed of the input shaft is reduced relative to the output shaft, the torque on the helical splines will reverse. Thus, causing the sliding component to return to the disengaged position. The clutch output will overrun the clutch input resulting in the SSS clutch "freewheeling". The described SSS Clutch can operate continuously engaged or overrunning at maximum speed without wear occurring [32].

2.3.1. Effects of Clutch Engagement

The most important effect of the clutch engagement that needs to be considered is on the automatic voltage regulator (AVR) excitation of the SC. When the clutch disengages, the excitation system of a SC needs to be adjusted to maintain the desired voltage and reactive power output. The excitation system controls the magnetic field of the SC, which in turn determines the reactive power output [35].

If the clutch disengages, the mechanical power input to the SC is reduced or lost, which causes the rotor speed to decrease. As a result, the excitation system must increase the field current to maintain the voltage and reactive power output [36].

The exact adjustment required will depend on the specific design of the excitation system and the characteristics of the SC. In some cases, the excitation system may have a feedback loop that adjusts the field current based on measurements of the voltage and reactive power output [36]. In other cases, the adjustment may need to be made manually by an operator.

It is important to note that the adjustment of the excitation system should be done carefully to avoid overexcitation or under excitation of the SC, which can result in instability or damage to the equipment. AVR is one of the core components of an SC to keep voltage stability [37].

Sebastián and Alzola [38], conducted a study to simulate the effects a friction clutch transition has on high penetration wind-diesel system. The idea being was to simulate the transition from wind-diesel (WD) to wind-only (WO) and what effects the clutch transition process has on the system stability. Sebastián and Alzola [38] concluded that the clutch transition has effects on both grid frequencies and RMS voltage.

2.3.2. Applications of SSS-Clutch in Power Systems

In power systems, SSS clutches are commonly used in applications where it is necessary to connect or disconnect rotating equipment quickly and efficiently, such as in emergency backup generators. In electrical power systems they are mainly used as an engagement source of a prime mover to the grid to provide active power [32]. When the prime mover is detached, the synchronous machine is then supplying reactive power and inertia to the grid for various reasons. These being power factor correction near highly inductive loads (industrial plants) or grid stability [39].

A current application of a SSS clutch used for SC is the GE LMS100 Gas turbine generators. In this application an encased SSS clutch was installed between the 100MW gas turbine and the generator to allow synchronous condensing duty of the generator [19]. Additionally, another example of a SSS clutch being used to enable SC applications was a retrofit at CFE's Universidad Power Plant in Mexico. A proposal was made to retrofit a retiring gas turbine unit with a SSS clutch to allow synchronous condensing duties. The repurposing of the turbine reduces limitations on the local power supply which allowed growth of the industrial base [19].

2.3.3. SSS-clutch Models in Simulink

In addition to the above *Section 2.2.3*, Simulink is a powerful simulation tool that can also be used to model and simulate the behaviour of an SSS clutch. Various libraries exist in Simulink that provide several blocks that can be used to create an SSS clutch model. However, a more in-depth and specialised model may be needed to produce accurate results of the effects a SSS clutch can have on power system characteristics.

To create an SSS clutch model in Simulink, various mechanical properties of the clutch which may include moment of inertia, damping coefficients, and friction coefficients need to be defined. Initial conditions for the clutch such as the initial angle and velocity also need to be set for accurate simulation.

Once the parameters and initial conditions are set, the SSS clutch model can be connected to the rest of the model, including the powertrain system and the control system. The clutch can be controlled by varying the input signals to the control system, such as the engine speed.

The experiments carried out by Chen et al. [31], resulted in a time-domain calculation method to calculate and analyse the torque impact and torque response of a SSS clutch engagement process in a Combined Gas Turbine and Gas Turbine (COGAG) device *(App. 3)*. In this study MATLAB was the preferred simulation tool used to simulate the effects of this engagement process due to the software's ability to manage complex mathematical models.

In addition to Chen et al. [31], the studies conducted by Tian et al. and Li et al. [33, 34] both used Simulink as the main software to simulate the effects of the SSS clutch engagement process. The studies resulted in Simulink models that produced results that were in line with the kinematic laws of a SSS clutch. Resulting in mathematical models that can be used for more in-depth studies.

2.4. Diesel Generation

Diesel generation refers to the use of diesel-powered generators to produce electricity in a power system that can be represented as a prime mover and a generator [40]. Diesel generators are often used as backup power sources in case of power outages, or in remote areas where it may not be practical to connect to the grid [41].

In power systems, the use of diesel generation can provide several benefits, including:

- Reliability: Diesel generators can provide backup power in case of outages or emergencies, ensuring that critical systems remain operational.
- Independence: Diesel generators can operate independently of the grid, providing power to remote locations where it may not be practical to connect to the main power network [41].

However, diesel generation also has several drawbacks, including:

- Cost: Diesel generators can be expensive to purchase and operate, particularly when fuel prices are high [20].
- Pollution: Diesel generators emit pollutants such as nitrogen oxides, particulate matter, and carbon monoxide, which can be harmful to human health and the environment [20].
- Maintenance: Diesel generators require regular maintenance to ensure they remain operational and efficient [42].

2.4.1. Diesel Generation and Renewable Energy

The inherent intermittency that comes with renewable energy has detrimental effects to how a conventional diesel generator unit operates. The sudden high ramping and frequent startups cause by the variable nature of renewable energy sources couple with changes in load cause these difficulties [10].

There have been various attempts of optimising the integration of diesel generation into remote hybrid power systems. In a study conducted by Hamilton et al. [41], it was found that the removal of energy storage devices accompanied with the adoption of partial load variable speed operation of a diesel generator improved efficiency of the engine and reduced low load emissions whilst also maintaining relatively similar amount of renewable penetration. Further suggesting that the optimal performance was observed in low to medium penetration systems where the requirement of battery storage was removed without significant performance penalty [41].

Moreover, Gatta et al. [20] conducted a study on the Giglio Smart Island Project which found that stage 2 of the project seen the replacement of the diesel generator with a properly sized and operated BESS and a SC to safely operate the network. Furthermore, Gatta et al. [20] also stated that dynamic simulations evidenced that in order to avoid trips due to high ROCOF from renewable energy, the installation of a SC with a large inertia was critical.

Overall, the use of diesel generation in power systems can be beneficial in certain situations, but it is important to carefully consider the costs and environmental impacts before deciding to implement this technology.

2.5. Conclusions

In conclusion, it is clear that there has been various works in the field of SC and SSS-clutches. However, more research needs to be conducted to consider the practical implications with a SC retrofitted diesel generator. Specifically what mechanical, control and economic issues may arise in the retrofitting process and what effects operation of the clutch has on grid characteristics. There has been limited research of the clutch engagement process and what effects it has on the grid. The clutch transition potentially has an effect on grid frequency and rms voltage as stated above, however more research needs to be conducted on the effects of the clutch engagement process has on existing AVR excitation systems and variations in torque from the prime mover.

In addition, it is clear that there are copious amounts of research regarding current protection systems and the negative impacts higher DER penetration has on these protection schemes. There needs to be more research into the solutions for this problem and whether or not a SC retrofitted DG is a viable solution for microgrid and isolated system support when comparing to the current DG integration methods. The need for grid support from synchronous machines is potentially crucial to the advancement of microgrids and isolated systems enabling companies to supply customers with reliable and safe power generation.

3. Methodology

A simulation-based research approach will be conducted for this thesis to simulate and analyse the effects an application of an SC in a diesel generator may have on microgrids and isolated systems. There are various methods of software to achieve this, these being: PSCAD, RSCAD, MATLAB Simulink and Power Factory.

The chosen software for this project is MATLAB Simulink due to its ease of use, and the supply of various advanced toolboxes for specialized power system simulation. Simulink can be used to simulate the behaviour of the effect an SC and an SSS clutch engagement process has on an isolated system under different operating conditions and to analyse its performance in the power system. Simulink can also be used to design and test control strategies for the SC to improve its performance in the power system.

3.1. Objectives

This thesis project focuses on the various new challenges facing renewable energy dominant microgrids and isolated systems:

- The reduction of inertia and fault current in the electrical grid due to the decrease of conventional synchronous machines such as diesel generators limits the grid's ability to maintain energy balance and grid stability under fault conditions.
- Distributed energy resources (DER) are not able to provide the same fault contribution as traditional synchronous machines, resulting in integration issues with existing protection schemes.
- The lack of government regulations to allow DER's to provide reactive power to the electricity grid resulting in voltage instability.
- The potential effects a clutch engagement/disengagement process may have on the AVR excitation system or overall grid characteristics.

The following objectives outline how this project aims to show if a synchronous condenser based on a diesel generator's alternator is a viable solution for DERs dominated isolated systems:

- To address the lack of grid stability from the reduction of system inertia in "diesel off" mode, this project aims to simulate how the SSS clutch can detach a conventional diesel engine from the alternator resulting in the generator acting as an SC providing stability to the grid.

- The lack of fault current from renewable energy will be addressed by the implementation of the detached generator acting as an SC, which can provide fault current capability to operate standard protection systems designs.
- Finally, consider the implications to retrofitting SC functions to existing DGs. Specifically what effects the SSS clutch disengagement and engagement processes have on existing DG excitation systems.

To simulate the effects of the SC application in a diesel generator for electricity grids and isolated networks, a total of two Simulink models will be developed and simulated. The two models are as follows:

- Simulink Model with a diesel generator present to simulate a traditional electricity grid or isolated system.
- Simulink Model with a diesel generator and SSS clutch present.

These models will be tested under various operating scenarios that could happen on a daily basis such as:

- 30kW load switching – to simulate normal daily load switching processes.
- 200ms three-phase fault – to simulate worst case scenario effects on the grid. (Considering no influence from protection schemes)
- Clutch engagement/disengagement process – to understand how this affects the electricity grid and DG excitation system.

In summary, the focus of this thesis project is to explore if a SC retrofitted DG is a viable solution for small isolated systems to address these identified problems above when compared to the current method of DG integration. In addition, this project also aims to find the impact of the integration of an SC into an DG with the use of an SSS clutch and what effects this may have on the AVR control system.

3.2. Operating scenarios

3.2.1.30kW Load Switching

Load switching is a crucial aspect of electricity grid management and plays a pivotal role in ensuring grid reliability, stability, and efficiency of a power system. A comparison between how a conventional diesel generator and a synchronous condenser react under this condition is crucial in determining whether an SC is a viable solution to an isolated system.

3.2.2.200ms Three-Phase Fault

The three-phase fault element of this model below in *Figure 4* will be the main driver to see how the proposed Simulink model responds under fault conditions. Data describing the fault current, voltage stability and grid frequency will then be aggregated and analysed to understand the different effects a synchronous condenser and a diesel generator offer.

3.2.3.Clutch Engagement/Disengagement

The effects a SSS clutch may have during the engagement/disengagement process is key to understanding what effects this process has on the AVR excitation and prime mover torque variations. Specifically focusing on what happens to the AVR excitation when the clutch engages and disengages and how to control the AVR during this process. This will potentially determine whether a SC can be a viable solution for isolated networks under various operating conditions when comparing to a current integration of a DG.

To determine whether or not an SC is a viable solution for the above operating conditions of an isolated system, several crucial characteristics need to be considered such as:

- Grid frequency
- Grid voltage
- Synchronous machine output current
- Synchronous machine active power output
- Synchronous machine reactive power output
- Synchronous machine rotor speed
- Synchronous machine field voltage

Using these crucial characteristics, a better understanding of how an SC responds under certain operating conditions will be gained. Resulting in a more informed decision on whether or not a SC is a viable solution for isolated electricity systems when compared to the current method of diesel generators.

Overall, the key to verifying the objectives stated in *Section 3.1* using the above Simulink models is to have a clear understanding of the objectives, create accurate and representative electricity grid models, and use the simulation and analysis tools Simulink and RSCAD provide to evaluate and refine the models until they meet the performance criteria.

3.3. Simulink Model

Multiple MATLAB Simulink toolboxes were integrated into the production of a Simulink model. The final Simulink model used for this thesis is shown in *Figure 4*. This model consists of a diesel generator, line impedances, a 50-kW grid load, a 30-kW load with a circuit breaker, a 3-Phase fault, and a grid connection that is based on a 60Hz system.

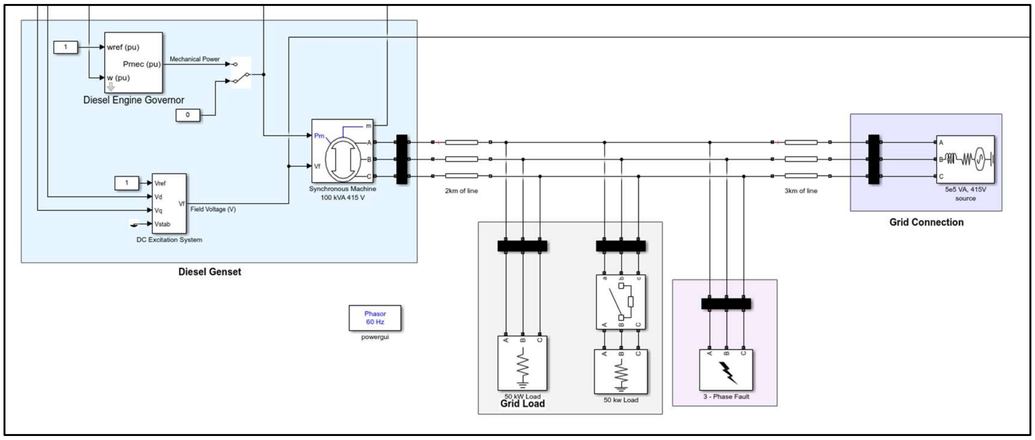

Figure 4: Final Simulink model.

3.3.1. Diesel Generator and Synchronous Condenser Model

The above Simulink model has a diesel generator present on the far-left side. The way a SC was simulated using this model was done by having a mechanical switch present on the mechanical power input of the synchronous machine (SM). This results in the model having the ability to simulate a clean drop in mechanical torque input, which simulates the diesel engine detaching from the SM (*Fig 5)*.

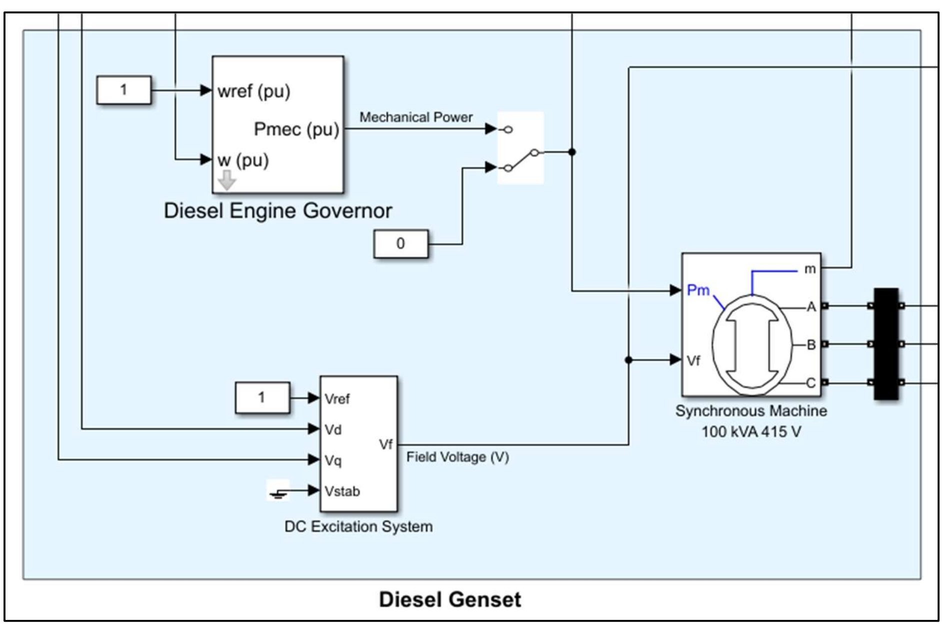

Figure 5: Final Simulink model diesel generator component.

The Synchronous Machine pu standard block models a SM in generator or motor mode using standard parameters in pu units [43]. The operating mode is dictated by the sign of the mechanical power (positive for generator mode or negative for motor mode). The electrical part of the machine is represented by a sixth-order state-space model and the mechanical part is the same as in the Simplified Synchronous Machine block [44]. The block has 2 inputs, mechanical power at the machine's shaft, in pu (P_m) and the field voltage (Vf), in pu which is supplied by a voltage regulator in generator mode. Moreover, the block has 4 outputs, m is a 24-element vector of measurement signals while the A, B, and C outputs are the separate phase outputs.

Furthermore, another block present in the diesel generator model is the Diesel Engine and Governor [45]. The governor plays a pivotal role in regulating the engine speed and ensuring it operates within desired parameters. Whether it is a large marine engine propelling a ship or a small generator providing backup power, the governor is the primary source of stability, maintaining the engine RPM under varying loads and conditions. The first input is the reference speed (ω_{ref}), and the second input is the measured speed (ω) . The output is the diesel engine mechanical power (P_{mec}). The motor inertia was combined with the generator inertia.

The model consists of a regulator represented by the following transfer function:

$$Hc = \frac{K(1+T3s)}{(1+T1s+T1T2s^2)} \qquad \text{- (1)}$$

In addition, the throttle actuator is implemented as:

$$Ha = \frac{(1+T4s)}{s\,(1+T5s)(1+T6s)} \qquad \text{- (2)}$$

The final block present in the model is the excitation system of the diesel generator. This block will be focused on in this thesis and how the clutch transition affects the blocks excitation output. The excitation system is a crucial component responsible for producing and regulating the stators electrical field required for the generator output. This system plays a pivotal role in maintaining voltage stability, load sharing, and the ability to respond to sudden changes in electrical demand.

The excitation system block implements an IEEE type 1 synchronous machine voltage regulator combined with an exciter [46]. The output of the block is the field voltage V_{fd}, in pu, to be applied to the V_f input of a SM block. In addition, the V_d and V_q measurements signals of the SM block are connected to the V_d and V_q inputs of the Excitation System block.

The exciter is represented by the following transfer function between the exciter voltage V_{fd} and the regulator output e_f:

$$\frac{V_{fd}}{e_f} = \frac{1}{K_e + sT_e} \qquad - (3)$$

where, K_e and T_e are the exciters gain and time constant, respectively.

3.3.2. SSS Clutch Implementation

The most challenging part of this project is the application of a SSS clutch model in the Simulink simulation and how the integration of the clutch can be performed correctly. A crucial element of this project is to simulate the effects an SSS clutch can have on the system through the engagement and disengagement processes. Various clutch block models are present within Simulink toolboxes, however with further analysis conducted it was decided to perform a more primitive approach and ignore the clutch dynamics for this thesis.

A manual switch was used to simulate the detachment of mechanical power to the SM. This provides a step change output, which is deemed a worst-case scenario transition. The Manual Switch block is a toggle switch that selects one of its two inputs to pass through to the output [47].

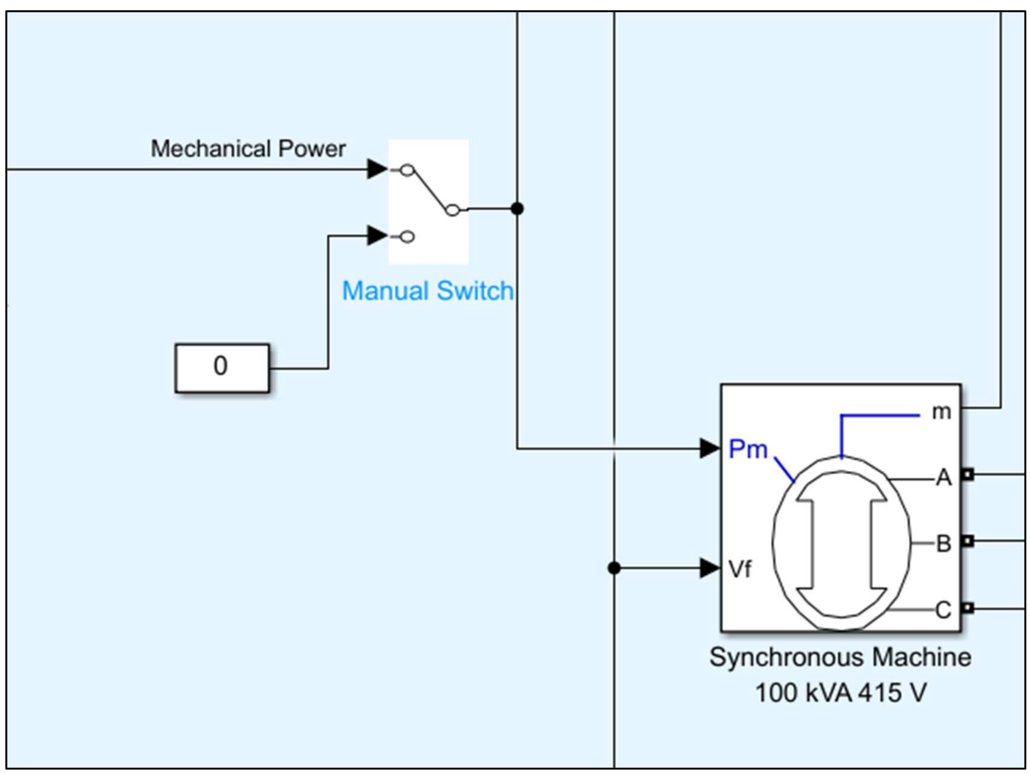

Figure 6: SSS Clutch implementation in diesel generator.

3.3.3. Grid Load Connection

The loads were modelled using three-Phase Parallel RLC block which represented a three-phase balanced load as a parallel combination of RLC elements. At the specified frequency, the load exhibits a constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage [48].

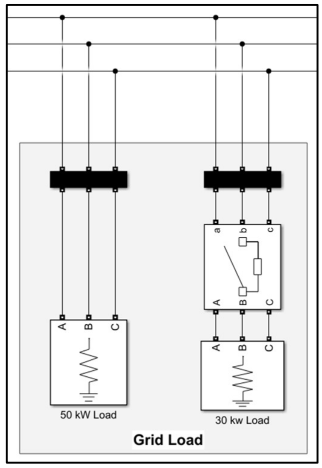

Figure 7: Grid loads in the Simulink model.

The grid load connection was implemented in two separate stages. The first is a purely resistive constant grid load of 50kW, which is roughly half of the generator capacity. In addition, there is another resistive 30kW grid load present with a circuit breaker integrated to allow switching of the load to simulate normal switching conditions on the electricity grid.

3.3.4. Fault Connection

A three-phase fault is a critical event in electrical power systems that occurs when a simultaneous and balanced short circuit occurs across all three phases. This type of fault is a serious concern for power engineers and utility operators because it can lead to significant disruptions, equipment damage, and even blackouts if not managed effectively.

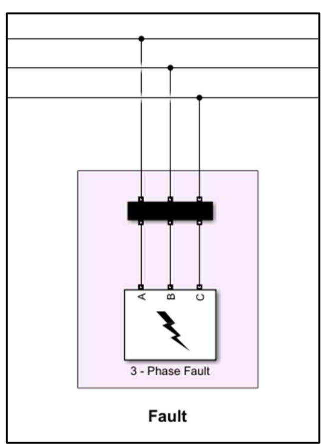

Figure 8: Three-phase fault in Simulink model.

The Three-Phase Fault block implements a three-phase circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode) [49].

The Three-Phase Fault block uses three Breaker blocks that can be individually switched on and off to program phase-to-phase faults, phase-to-ground faults, or a combination of phase-to-phase and ground faults. The arc extinction process of the Three-Phase Fault block is the same as for the Breaker block. The final fault resistance was set to 0.005 Ohm with a snubber resistance of 1e6 Ohm.

3.3.5. Grid Connection

Grid connection is a vital component of modern infrastructure that plays a pivotal role in the efficient distribution of electricity. This interconnected network of power lines and substations enables the seamless transfer of electrical energy from generation sources to end-users, ensuring a reliable and uninterrupted supply of electricity to homes, businesses, and industries.

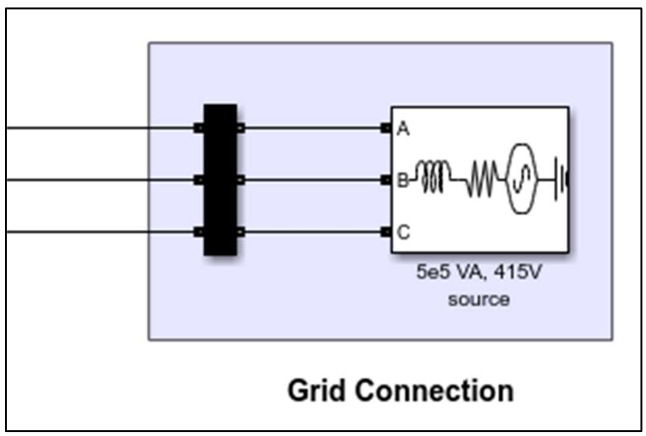

Figure 9: Grid connection in Simulink model.

The Three-Phase Source block implements a balanced three-phase voltage source with an internal R-L impedance. The block connects the three voltage sources in Y with a neutral connection that can be internally grounded or externally connected. The source internal resistance and inductance can be specified by either directly entering R and L values or indirectly by specifying the source inductive short-circuit level and X/R ratio [50].

The grid connection was modelled as a 500kVA source, resulting in the size being roughly 5 times larger than the diesel generator. This value was decided so the generator is not overpowered by an infinite bus during simulation. The X/R ratio is high when in close proximity to large generating stations and large substations. At the tail end of long distribution lines and for low voltage systems the ratio will be lower [51]. Hence, the X/R ration was chosen to be 10/1 to simulate a large generation point of the isolated power system.

3.3.6. Distribution Line Impedances

Finally, the diesel generator model in *Figure 5* also displays line impedances for each phase shown in *Figure 10*. This was done to simulate a more real-world problem that may have a length of electricity cables in between grid connections to simulate an isolated system. The lengths were chosen to be 2km and 3km to simulate a small electricity grid similar to what would be seen in an isolated network. The final values for line impedances used in the model can be found in Appendix 13.

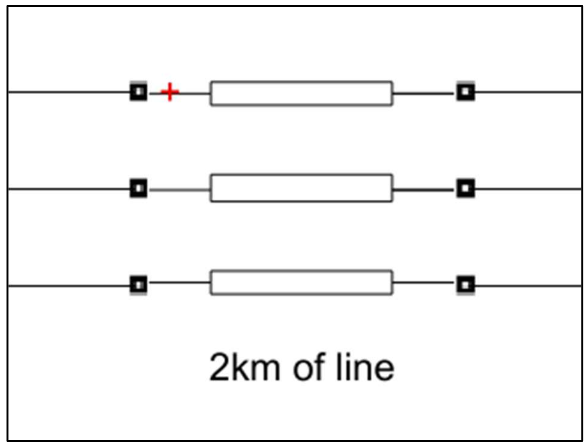

Figure 10: Line impedances in Simulink model.

4. Results and Discussion

4.1. Load Switching

Figure 11 shows a classic comparison between a DG and SC under load switching conditions. For this particular simulation, the grid is still connected, and the DG is outputting ~0.85pu of active power. It can be seen that the SC responds relatively similar to the DG under these conditions. When comparing the peak oscillation of both the DG and SC it is clear that the DG has a better response resulting in more ROCOF ride-through however, the SC still performs well under these conditions. In addition, the DG is able to return to steady state faster than the SC. These two results are due to higher inertia the DG inherits over the SC.

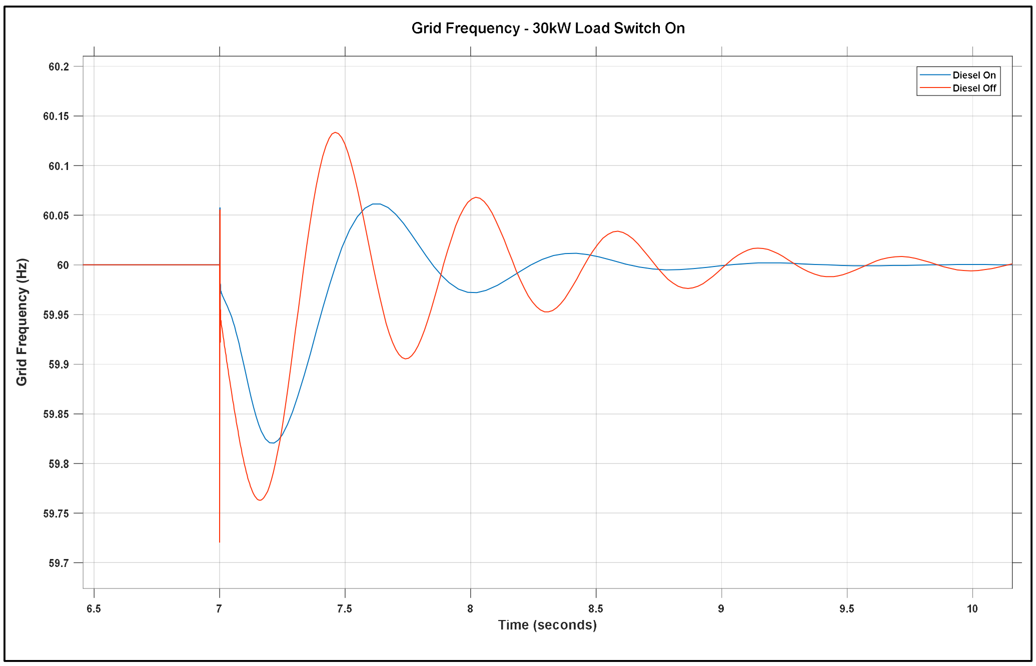

Figure 11: Comparison of grid frequency for 30kW load switch on.

The peak oscillation for the SC in "Diesel Off" mode is ~-0.23 Hz to ~+0.13Hz while the peak for the DG is ~-0.17Hz to ~+0.065hZ. Comparing these values there is very minimal difference when considering the magnitude of the oscillations. The SC has a maximum of ~0.38% change in frequency while the DG has a maximum of ~0.28% change in frequency.

The values of peak ROCOF for the DG and SC of 0.45Hz/sec and 0.72Hz/sec, respectively are below the regulatory maximum standard ROCOF of 1Hz/sec [52]. This suggests that a SC is able to provide the grid with suitable ROCOF when under daily load switching conditions.

Considering the results in *Figure 12* under the 30kW load switching condition, it can be seen that in both circumstances the DG and the SC are both able to provide voltage correction well. Interestingly enough, the SC actually outperforms the DG when returning back to a steady-state condition after the load switches on due to the less inertia in the SM system.

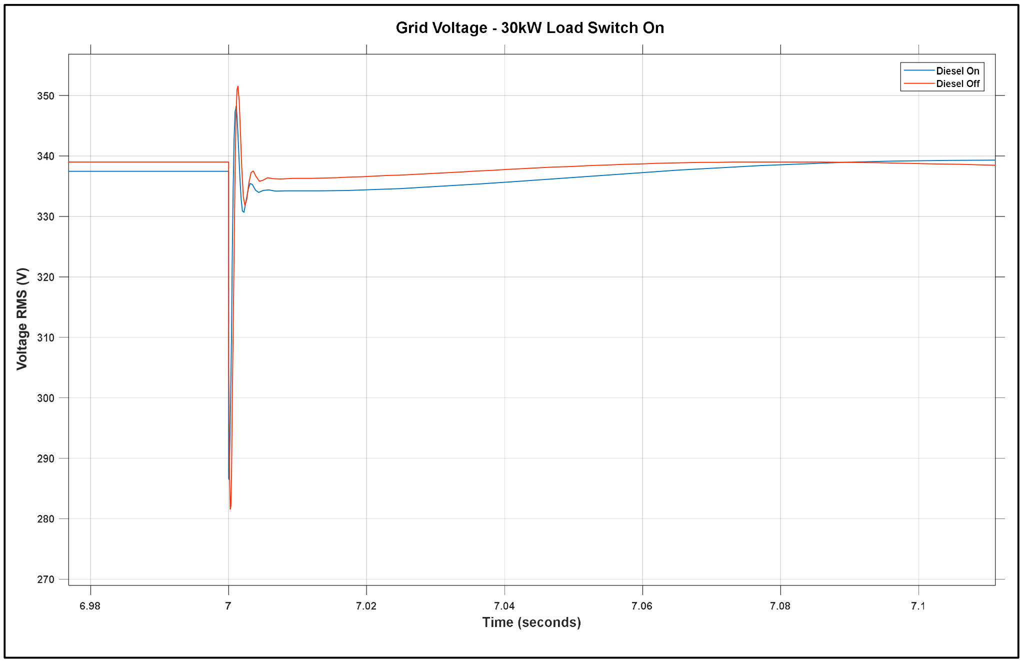

Figure 12: Comparison of grid voltage for 30kW load switch on.

From the figure the peak voltage drop for the SC is approximately 4V more than the DG. The SC peak drop is ~16.5% reaching approximately 282V while the DG drop is ~15.4% reaching roughly 286V. When considering a 4V difference between an SC and a DG operating at ~338V this is a very minimal difference in comparison. This suggests that a SC can in fact provide voltage support when load switching operations occur when comparing to the current standard DG integration methods.

Figure 13 is the SMs rotor speed under load switching operation. When considering the rotor speed of the SM, its critical to ensure the speed does not decrease to a level that cannot be recovered from. In conjunction with *Figure 13, Figure 14* shows the active power output of the SM, a crucial element to maintaining rotor speed of the SC. *Figure 13* is similar in output to *Figure 11* since the rotor speed and electrical frequency are locked in phase.

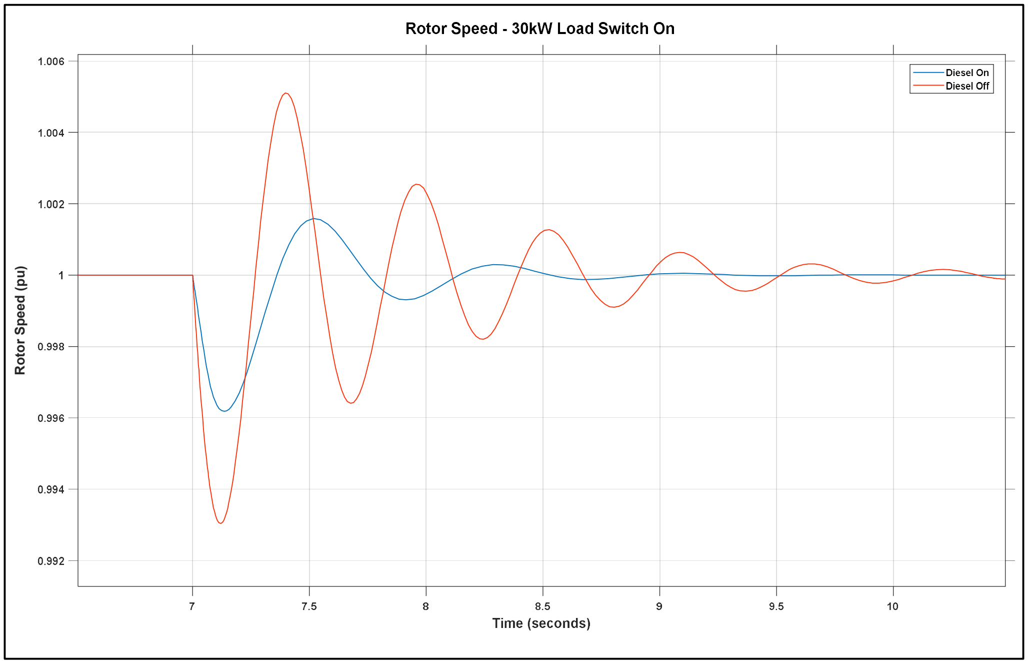

Figure 13: Comparison of SM rotor speed for 30kW load switch on.

When load switching occurs, the rotor speed for both the SC and DG reduce slightly which is to be expected. The peak drop in rotor speed is ~0.007pu for the SC whereas for the DG the peak drop is ~0.004pu.

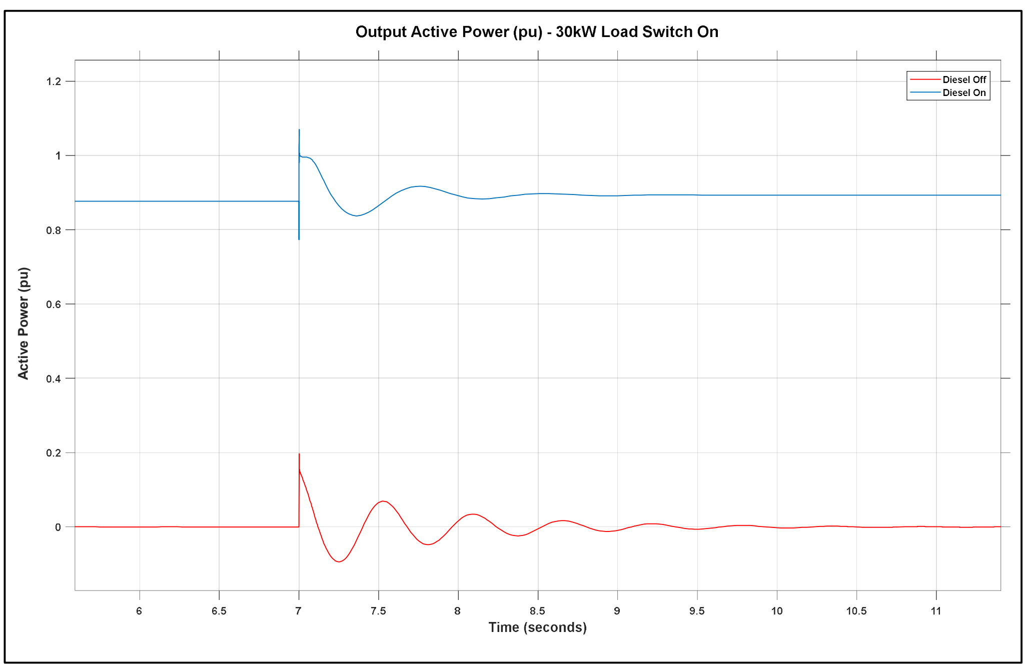

Figure 14: Comparison of SM output active power for 30kW load switch on.

However, when considering the SC rotor speed, since there is no prime mover attached, the SM must absorb power from the grid to stabilise the rotor speed back to steady state operation. As the rotor speed for the SC begins to increase, the output power in *Figure 14* begins to go negative, indicating that the SC is absorbing power from the grid to recover rotor speed. The absorption of 0.1pu is minimal power consumption and would not negatively affect grid conditions. This again suggests that the integration of a SC instead of a DG could potentially be a viable solution for high penetration DER isolate electricity systems when under daily load switching operations.

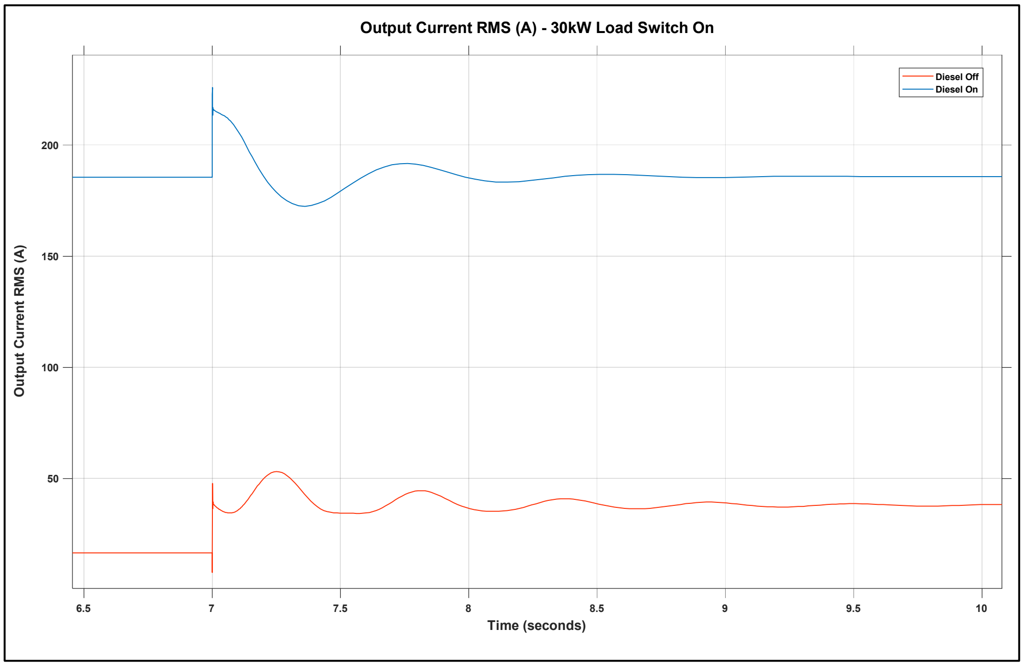

Figure 15: Comparison of SM output current for 30kW load switch on.

Finally, analysing *Figure 15* it is clear that the SC is able to provide current to the grid when under general load switch conditions. This is a crucial element to determining whether or not a SC may be a suitable option when considering to current DG operation. When comparing the SC to the DG, there is barely any similarity due to the difference the prime mover makes.

In conclusion, the comparative analysis presented suggests that a SC is a reliable alternative to current DG integration in high DER penetration grid scenarios with frequent load switching. While DGs exhibit slightly better performance in terms of ROCOF and faster return to steady state due to their higher inertia, SCs still meet regulatory standards for RoCoF and perform well in voltage correction during load switching events. Moreover, the ability of SCs to absorb minimal power from the grid to stabilise rotor speed and provide current support suggests that SCs could offer a viable and environmentally friendly solution in modern electricity grids when compared to current DG integration.

4.2. Three-Phase Fault

When analysing the effects of a three-phase fault has on the grid, there are several characteristics that need to be considered. *Figure 16* and *Figure 17* are comparisons of the overall and detailed response a DG and SC have under a three-phase fault condition. For this simulation, the fault described in *Section 3.3.4* is activated and then cleared after 200ms.

An analysis of Figure 16 presents the total response of the DG and SC. The responses suggest that the SC actually performs better under faulting condition when compared to the DG. The DG is able to return to steady state faster than the SC, however, the overall magnitude of frequency fluctuations tends to be considerably larger than the SC.

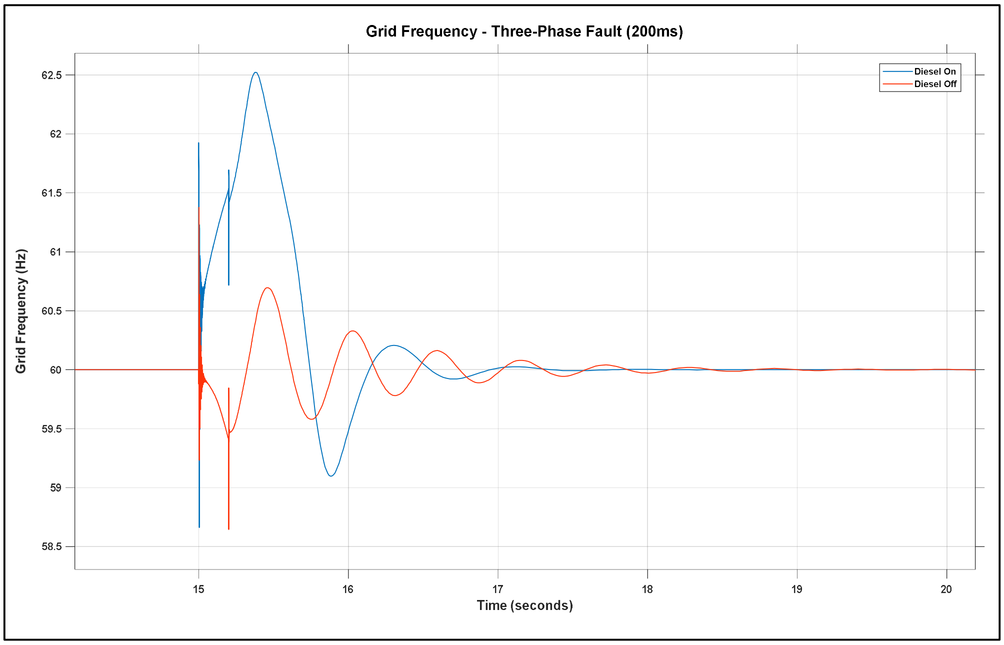

Figure 16: Comparison of grid frequency full response for three-phase fault.

The peak oscillation in frequency for the SC and DG are ~-0.6HZ to ~+0.7Hz and ~0.85Hz to ~+2.5Hz, respectively. This results in the Sc having a maximum of ~1% change in frequency while the DG has ~4.2% change in frequency.

A more detailed presentation of the grid frequency response under faulting condition is shown in *Figure 17*. There is a considerable difference in response from the SC when comparing to the DG. As to be expected, the grid frequency actually increases when the DG is active, and decreases when the SC is active. This difference is due to the absence of the engine governor for the SC, resulting in no rotor speed correction during the fault unlike the DG response. When analysing the ROCOF for a full three phase fault, both the peak ROCOF values of ~4.8Hz/sec and ~4.05Hz/sec for the DG and SC respectively are both above the maximum allowable ROCOF frequency of 1Hz/sec [52]. This could be due to the small nature of the isolated system under test.

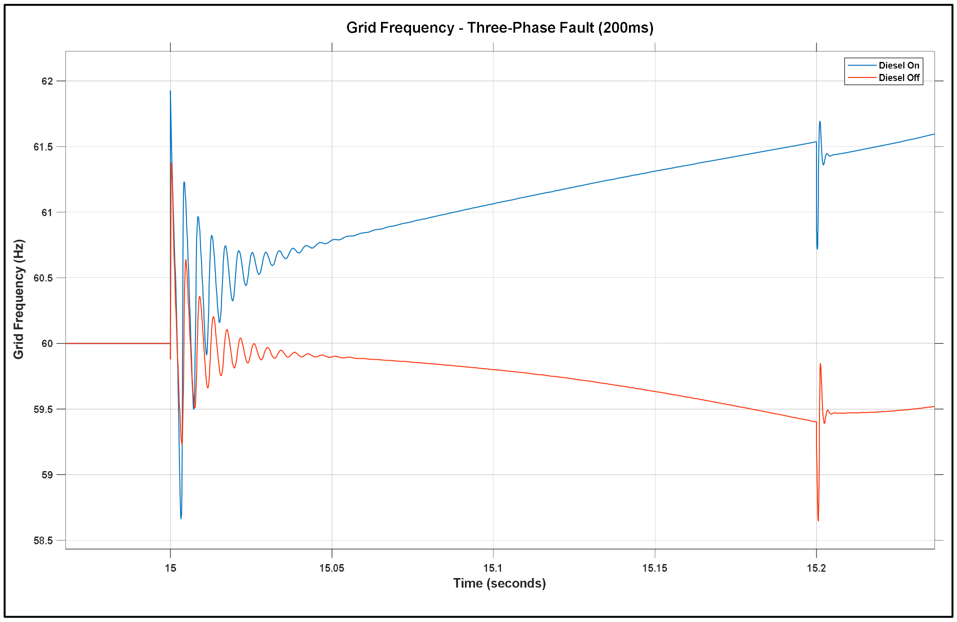

Figure 17: Detailed comparison of grid frequency for three-phase fault.

A closer look at *Figure 18* and *Figure 19* illustrates this response through the SMs rotor speed. A more detailed look at *Figure 18* shows that initially both the SC and DG have a small decrease in rotor speed when the fault first occurs. This is to be expected due to the large load on the system caused by the fault.

However, where the difference in response occurs is when the DG governor begins to respond and the rotor speed for the DG starts to increase while the SC is still on a relatively steady decline. These results suggest this is where the difference in grid frequency response comes from since the SM rotor speed directly affects the grid frequency.

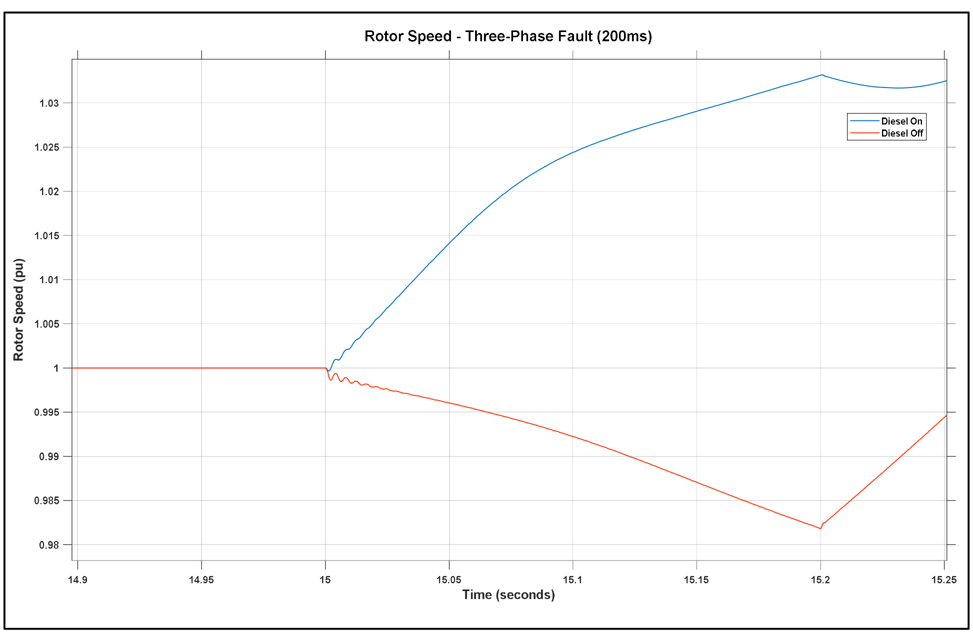

Figure 18: Comparison of SMs rotor speed detailed response for three-phase fault.

When considering the full fault response displayed in *Figure 19*, it is clear that the SC has a better response than the DG initially. However, the DG is able to return to steady state operation faster than the SC which is to be expected due to the added diesel engine and governor. Whereas the SC must consume and utilise power from the grid to steady the rotor.

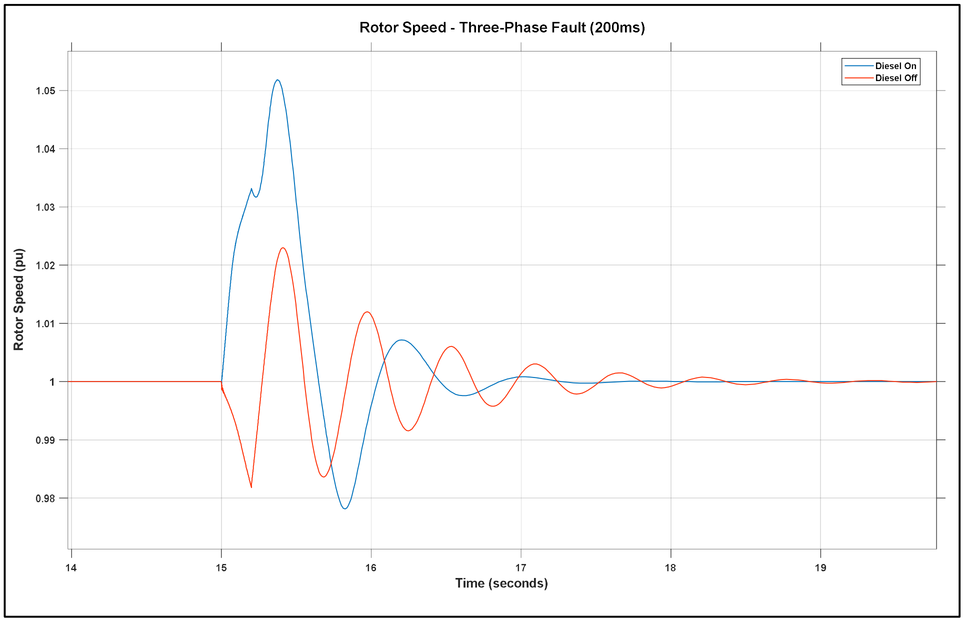

Figure 19: Comparison of SMs rotor speed full response for three-phase fault.

Voltage support is another crucial aspect that needs to be considered when investigating if a SC is a viable solution to replace a DG in a high penetration DER isolated network. Analysing *Figure 20* suggests that under a 200ms three-phase fault a SC is able to provide the necessary voltage support to the grid to ensure under voltage fault does not occur.

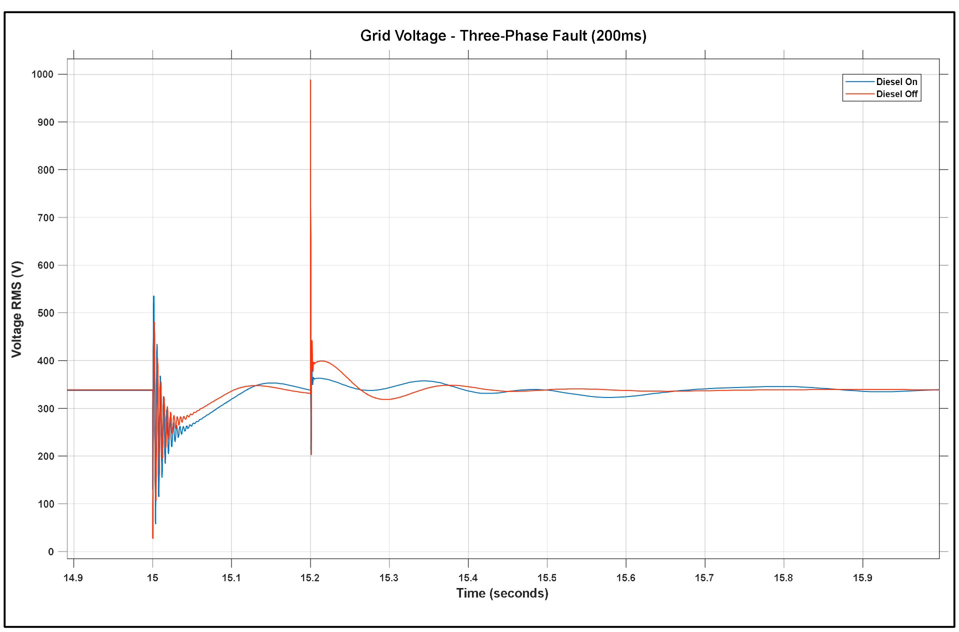

Figure 20: Comparison of grid voltage full response for three-phase fault.

Further analysis of *Figure 20* shows that the initial spike in voltage from the SC when the fault clears is much larger than the DG. The SC then fluctuates at a higher oscillation for a shorter period of time, while the DG has a more damped response that last for a longer period of time.

This is possibly due to the integration of the DG engine governor and exciter input into the SM, while the SC only has the exciter input into the machine. The SC exciter only has to maintain voltage and reactive power at the SM terminals while the DG has to perform that as well as the active power input into the grid resulting in a slightly longer period of time to achieve steady state.

A more detailed representation of the 200ms fault period is shown in *Figure 21.* This response suggests that initially the SC response with a higher voltage when compared to the DG. However, once the DG engine governor starts to respond it allows the DG to peak at a higher voltage than the SC just prior to the fault being cleared.

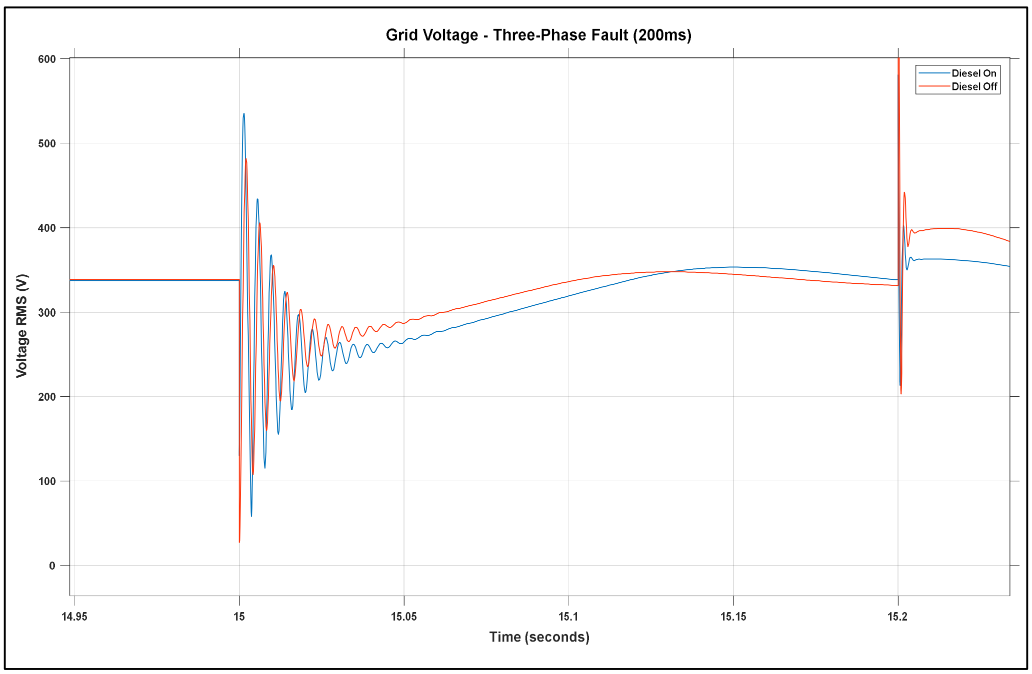

Figure 21: Comparison of the grid voltage detailed response for 200ms three-phase fault.

Furthermore, both the DG and SC respond relatively well to the initial fault, both providing the necessary voltage support to assist with fault ride through. The DG initially oscillates around ~250V while the SC oscillates around ~270V before they both steadily increase the grid voltage throughout the fault period. The SC has an initial voltage drop of ~20% while the DG has a drop of ~26% in voltage, which is a considerable amount.

Finally, perhaps the most critical aspect that needs to be consider when under faulting conditions is how much fault current the DG and SC are able to provide to the grid. The need for a large enough amount of fault current to operate current existing protection systems is a crucial aspect. Analysing Figure 22 the SC clearly performs well in this aspect, essentially matching the DG performance under the fault conditions. Similar to the grid voltage, the SC current output is slightly higher than the DG initially but then starts to decay over time once it reaches the peak.

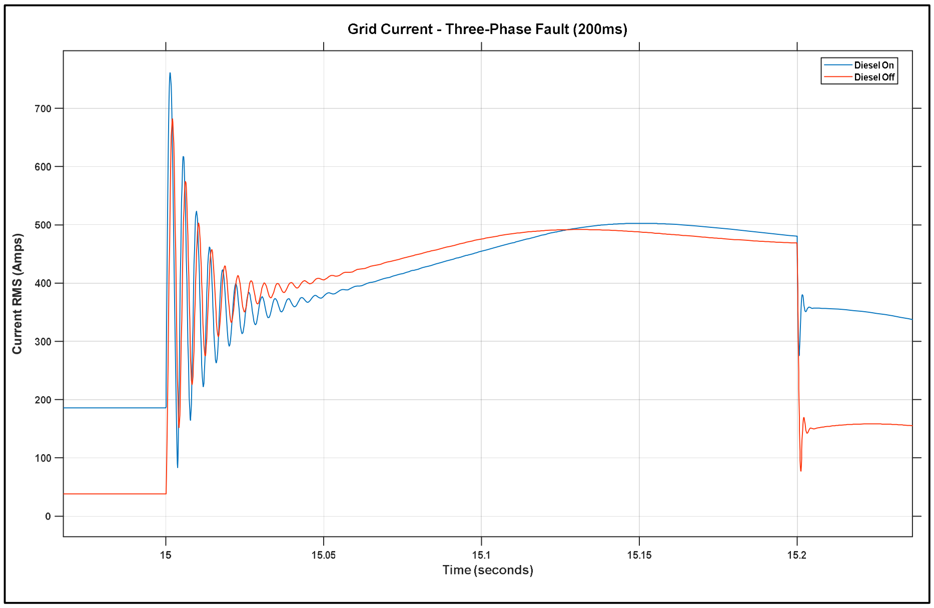

Figure 22: Comparison of the SM output current detailed response for 200ms three-phase fault

The DG has increase in current oscillating around ~350 A while the SC has an increase of current oscillates around ~390A Once the fault is cleared, both the DG and SC reduce in current output which is to be expected as the load suddenly decreases.

The comparative analysis of a DG and a SC under a three-phase fault scenario in *Section 4.2* reveals important performance distinctions. While the DG exhibits a quicker return to steady-state operation, it suffers from more significant frequency fluctuations and exceeds permissible ROCOF limits. This could be a result of the current governor tuning which may be altered to obtain a better response.

In contrast, the SC offers relatively moderate grid frequency stability, although it takes longer to recover. Voltage support also varies, with the SC providing a higher initial voltage spike and shorter oscillations when the fault is cleared, possibly due to the more simplified control system. Moreover, both the DG and SC perform well in supplying fault current to meet current protection system requirements. These findings highlight the complex trade-offs involved in choosing between DG and SC in high penetration DERs networks, with each offering advantages and disadvantages under different fault conditions.

4.3. Clutch Disengagement

When considering the SSS clutch detaching the diesel engine from the alternator to allow synchronous condensing, the effects on the wider network must also be considered. Moreover, it is also relevant to consider at what stage of power generation the engine lost. For this simulation worst case scenario was considered where the diesel engine is instantaneously detached at near full power generation.

A closer analysis a *Figure 23* shows a comparison between the input mechanical power for the SM and the output active power from the SM. It can be seen that the instantaneous drop in mechanical power input is simulating the SSS clutch detachment resulting in a loss of the input diesel engine. Furthermore, *Figure 23* also shows a large fluctuation in active power output when the engine detaches forcing the SM to actually absorb a relatively large amount of power from the grid. Tuning of the AVR excitation system may help improve performance.

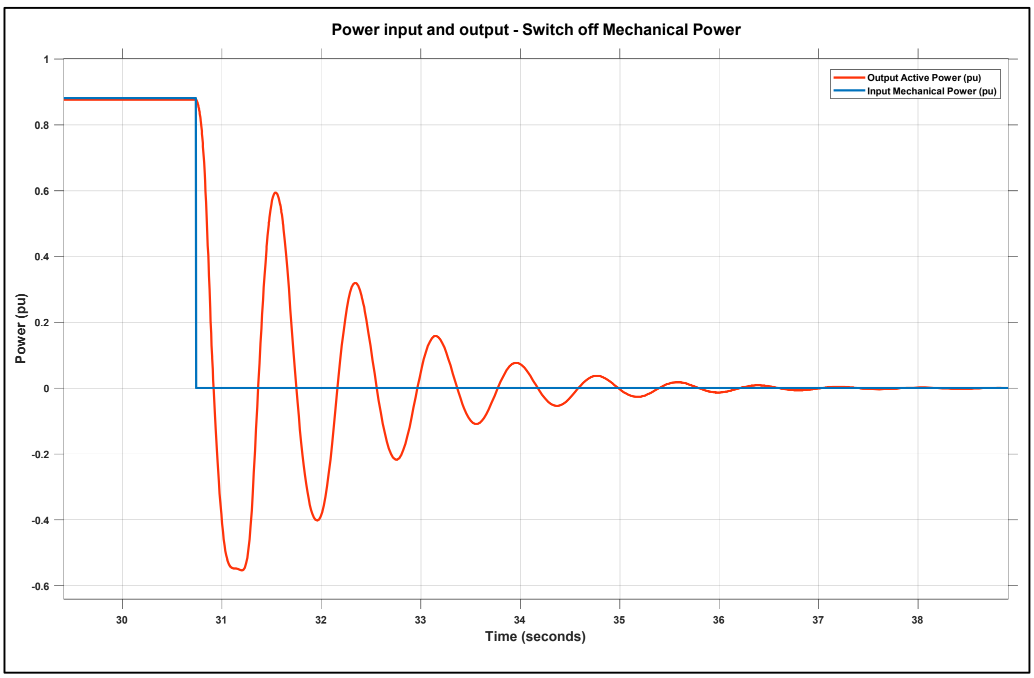

Figure 23: Input Mechanical and Output Active Power response to instantaneous diesel engine detachment.

As above in *Section 4.1* this is caused by the reduction in rotor speed the SM undergoes due to the loss of the diesel engine power input while the generator is under full load. The SM must absorb power from the grid to maintain rotor speed and return back to steady state operation. The initial change in power output oscillation is ~1.4pu, which is a rather large change in active power output. Eventually the active power output reaches steady state operation a 0pu active power output which is to be expected when the diesel engine detaches.

Figure 24 shows the characteristic of the rotor speed in more detail. The loss of SM rotor speed is relatively small only losing ~0.035pu in rotor speed initially. Once the SM absorbs power from the grid as shown in *Figure 23*, the SM rotor speed oscillates for a short time until steady state operation is reached at 1pu which is to be expected.

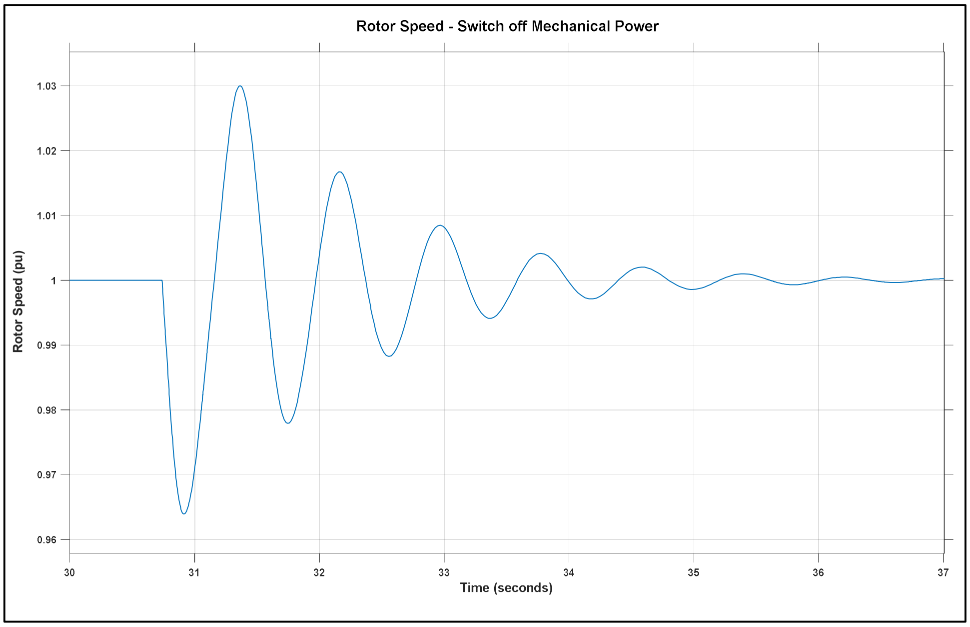

Figure 24: SM rotor speed response to instantaneous diesel engine detachment.

The effects the clutch detachment of the diesel engine has on the grid frequency is also another crucial aspect of this thesis. As above in *Section 4.1* the rotor speed of the SM and overall grid frequency are closely related. The grid frequency response for the SSS clutch detachment of the diesel engine is shown in *Figure 25*. The initial ROCOF is calculated to be ~7.4Hz/sec which is well outside of the maximum ROCOF regulations of 1Hz/sec. This could be due to the loss of mechanical power while the diesel generator is under full load.

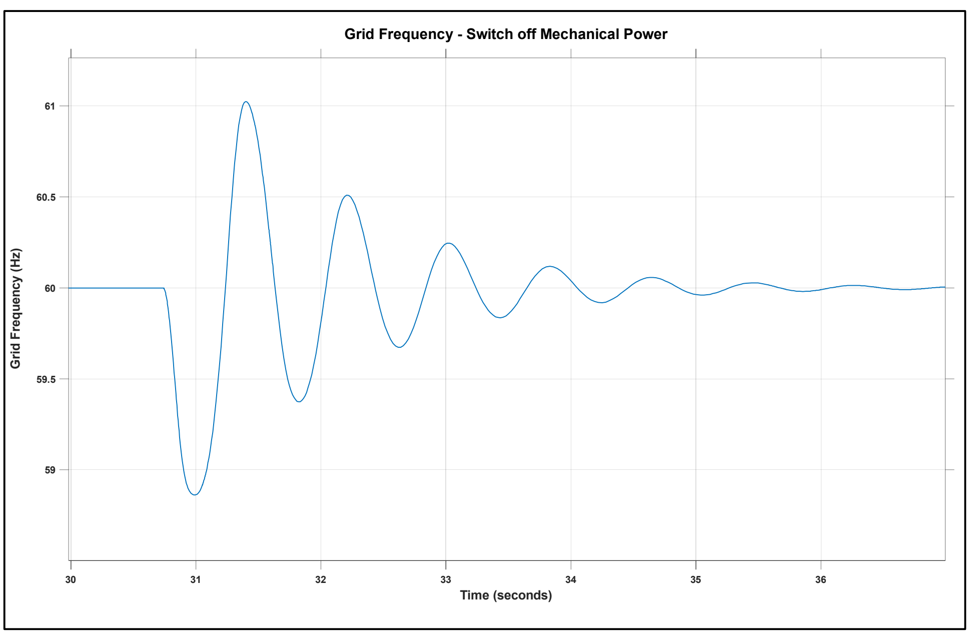

Figure 25: Grid frequency response to instantaneous diesel engine detachment.

Finally, one of the most important characteristics when considering a SC retrofitted DG with the use of an SSS-clutch is what effects the loss of the diesel engine has on the excitation system of the SM. As above, the excitation systems main priority is the regulate the voltage at the terminals of the SM by varying the excitation current apply to the stator windings.

Figure 26 shows the field voltage response to the diesel engine loss under approximately full load. Analysis of the response in Figure 26, the excitation system appears to be extremely unstable after the loss of the diesel engine having a peak oscillation of ~0.45pu to ~3.8pu which is relatively significant. The field voltage applied to the SM is able to reach steady state eventually, however more research is needed to determine whether current AVR systems are able to handle such responses. It is likely that current AVR systems with hit over/under excitation limits, which will change the response,

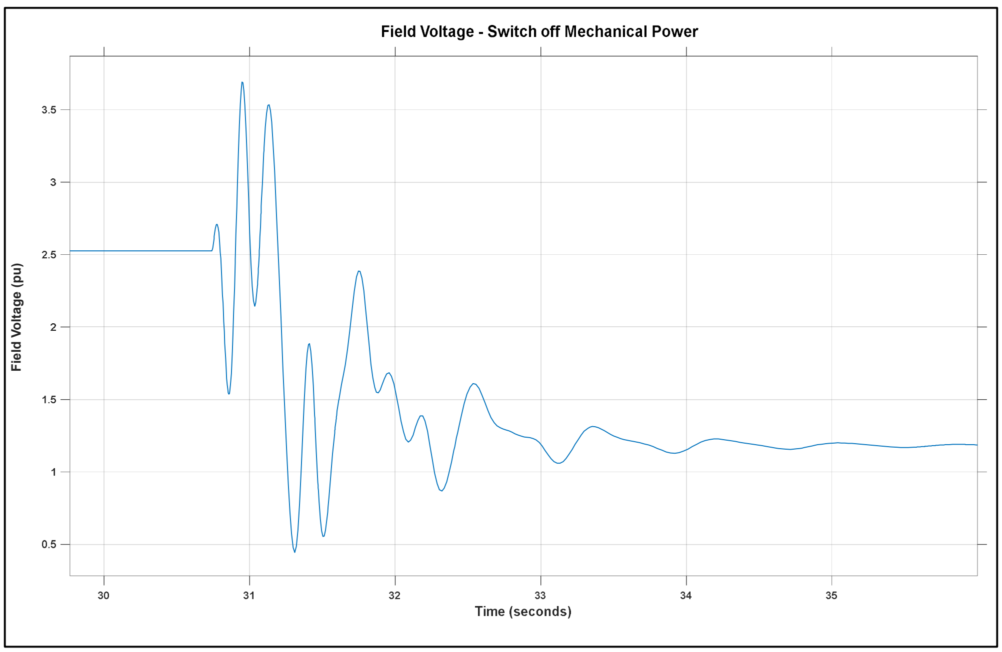

Figure 26: Field voltage for SM response to instantaneous diesel engine detachment.

Lastly, the resulting grid voltage response from the diesel engine detachment is shown in Figure 27. Considering the large oscillations in field voltage shown in Figure 26, the response of the grid voltage is relatively stable in comparison. The peak oscillations in grid voltage range from ~332V to ~345V with steady state being roughly ~337V. Since there is only a peak drop of ~1.5%, and a peak gain of ~2.4% in grid voltage, this would suggest that the instantaneous loss in mechanical power does not affect overall grid voltage drastically.

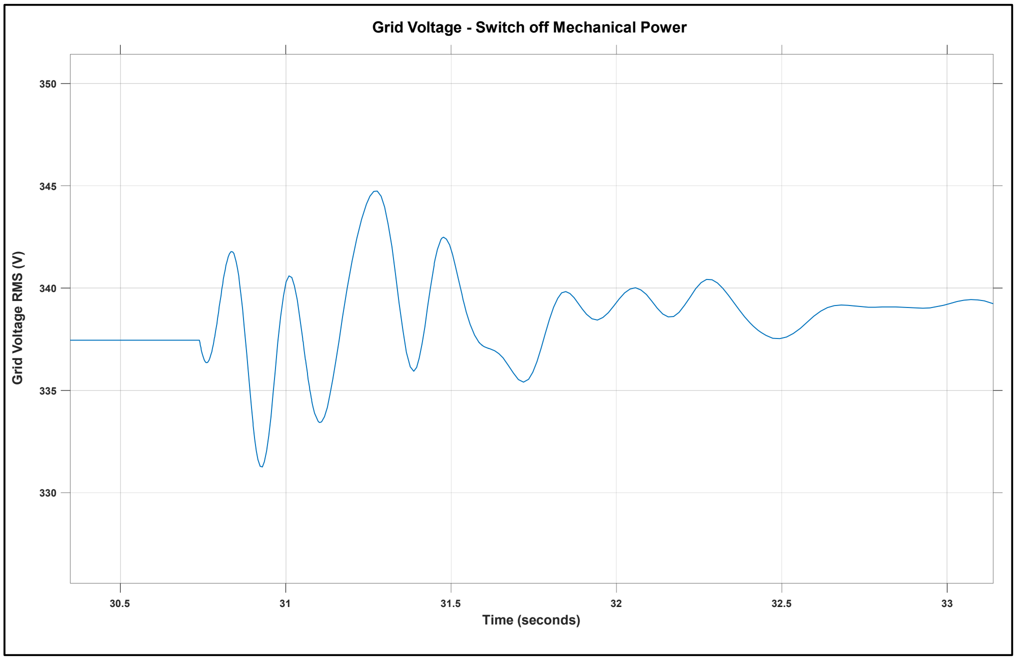

Figure 27: Grid voltage response to instantaneous diesel engine detachment.

Importantly, the study highlighted the substantial impact on grid frequency, with a calculated ROCOF exceeding regulatory limits, likely attributed to the loss of mechanical power during full load operation. Additionally, the excitation system's response appeared unstable, warranting further investigation. Despite these challenges, the grid voltage exhibited relatively stable behaviour, suggesting that the instantaneous loss of mechanical power may not have a drastic impact on overall grid voltage. Overall, this analysis underscores the complexity of integrating synchronous condensers with SSS clutches into conventional diesel generators, emphasizing the need for careful consideration and potential system enhancements when implementing such configurations.

4.4. Clutch Engagement

The final simulation performed to consider if an SSS-clutch can be retrofitted to a DG is how the system responds to instantaneous engagement of the diesel engine. When considering a real-life application of this process, the most demanding situation would be to engage and ramp up to maximum power output instantaneously. This is the simulation that has been simulated in this section.

Figure 28 displays this scenario with the power output of the SM over time. Analysis shows that the active power output increases from 0pu to just over 1pu in less than 500ms, this is incredibly demanding for the generator and engine. In addition, the reactive power also has a spike after a slight decline in reactive power output. Both active and reactive power outputs reach steady state operation at ~0.85pu and ~0.36pu respectively within 3 seconds from clutch engagement.

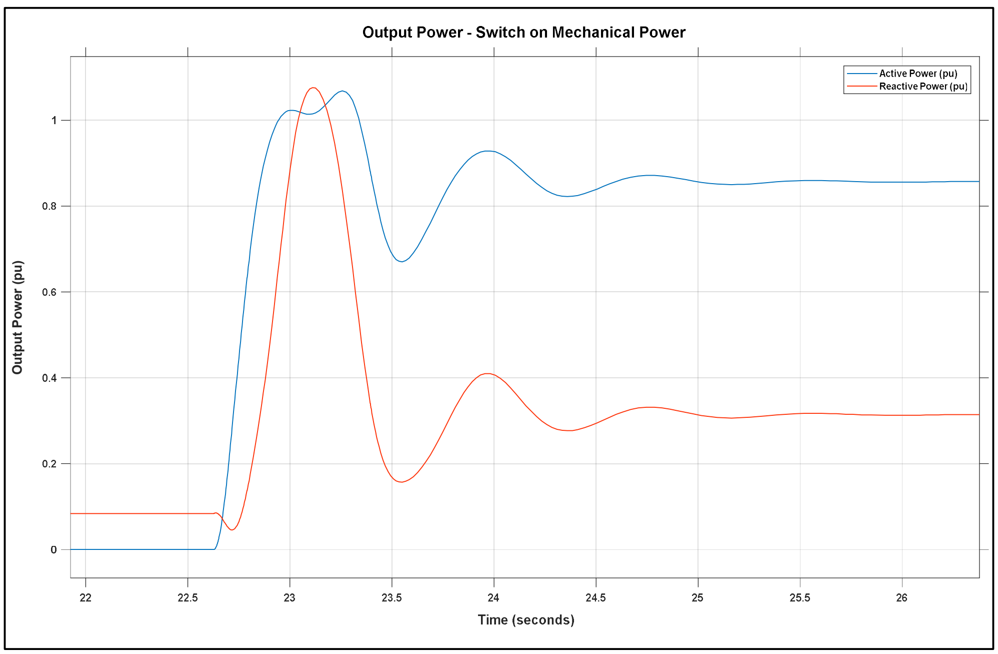

Figure 28: SM power output response to instantaneous diesel engine engagement.

Figure 29 and Figure 30 display the response of the excitation field voltage applied to the stator winding, and the overall grid voltage of the isolated system under simulation, respectively.

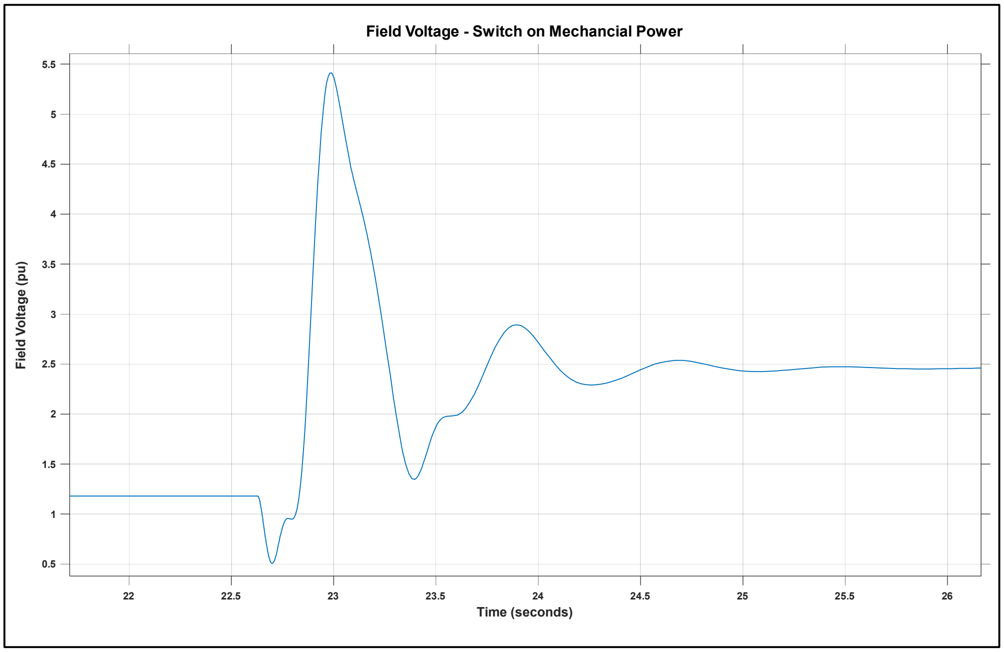

Figure 29: Field voltage for SM response to instantaneous diesel engine engagement.

Analysis of *Figure 29* shows the field voltage response under clutch engagement conditions is much more stable than clutch disengagement response shown in *Section 4.3, Figure 26*. Initially there is a small drop in field voltage applied to the SM before a major spike to ~5.5pu occurs and then eventually reaches steady state operation at ~2.5pu. This major spike in field voltage is due to the drop in grid voltage that can be seen in *Figure 30.* However, following this initial spike, the oscillating response is relatively stable when compared to the disengagement process eventually reaching steady state at ~2.5pu and ~337V, respectively.

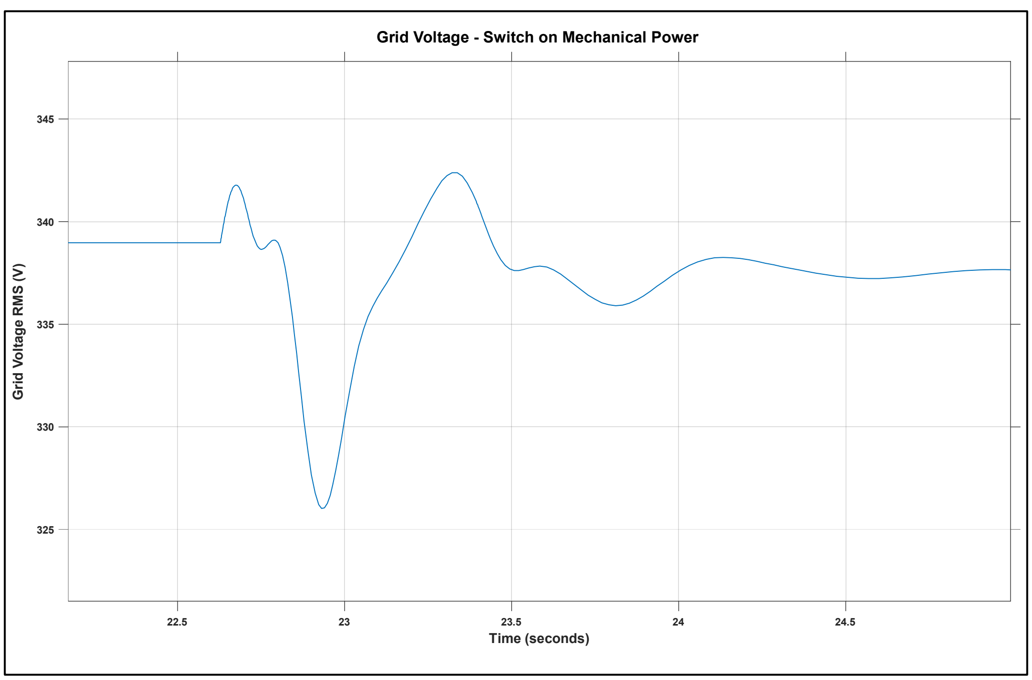

Figure 30: Grid voltage response to instantaneous diesel engine engagement.

Additionally, other characteristics that need to be considered in this section are the SM rotor speed, mechanical input, and overall grid frequency displayed in *Figure 31*, *Figure 32,* and *Figure 33.* This is important to see whether the clutch engagement has any disturbance on the overall grid characteristics.

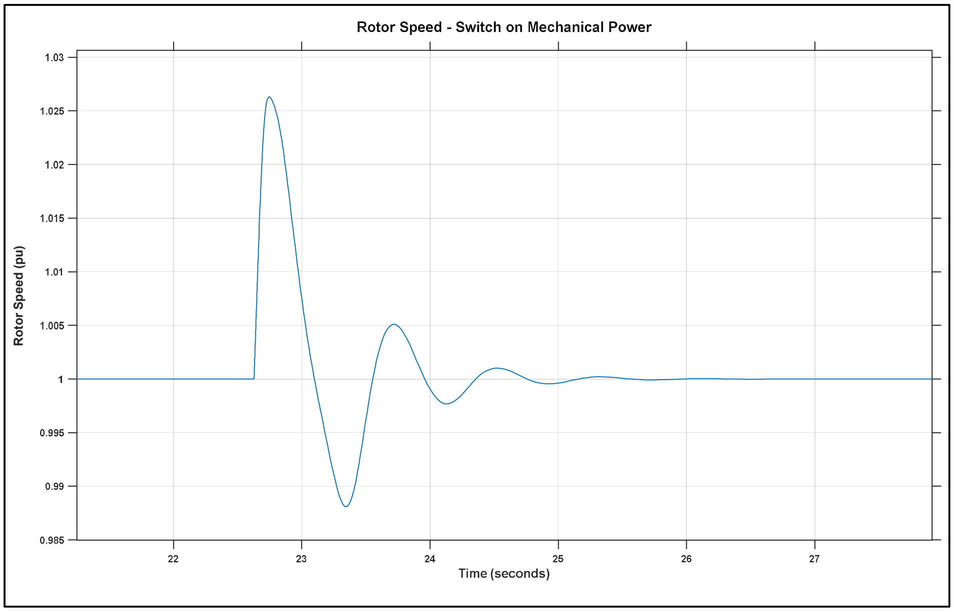

Figure 31: SM rotor speed response to instantaneous diesel engine engagement.

Examining *Figure 31* displays that the SM was initially spinning in synchronisation with the grid. Following this, a steep initial spike in SM rotor speed occurs when the clutch is initially engaged. The rotor speed eventually reaches steady-state operation around 3 second later; this is due to the change in mechanical power from the diesel engine governor response shown in *Figure 32*.

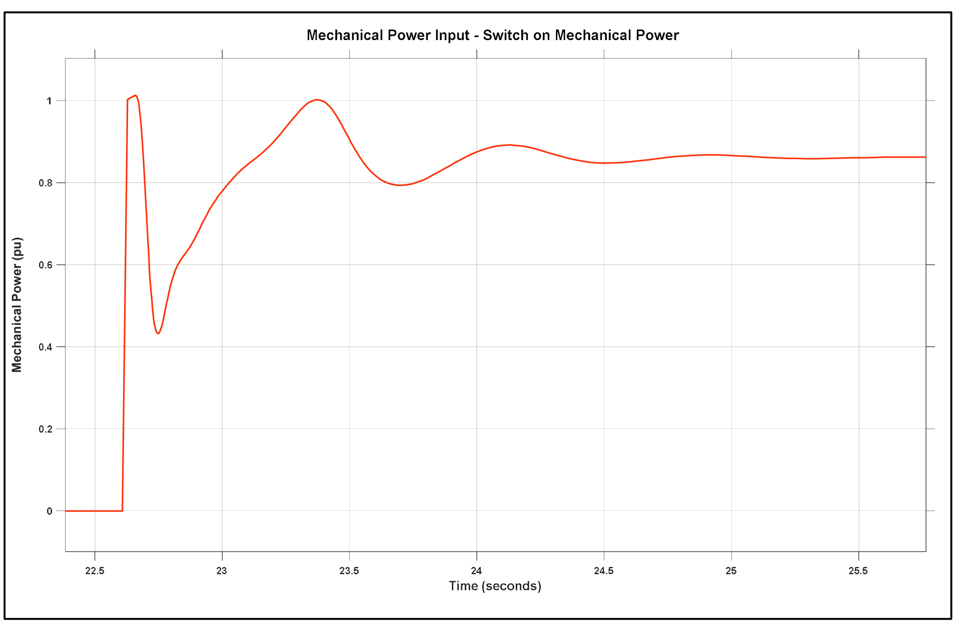

Figure 32: Mechanical Power input for SM response to instantaneous diesel engine engagement.

Moreover, it is clear that the initial mechanical input for the generator may be too high, so the governor responds to the rotor speed spike by dropping the mechanical power input. Following this both the governor response and rotor speed are able to stabilise at ~0.85pu and 1pu in a relatively short period of time.

Lastly, *Figure 33* illustrates the grid frequency response for the clutch engagement process. When comparing to the clutch disengagement process the resulting magnitudes of oscillations are relatively similar however the clutch engagement process shown below reaches steady state operation faster. The initial ROCOF spike is ~4Hz/sec which is still outside the maximum regulatory limits of 1Hz/sec.

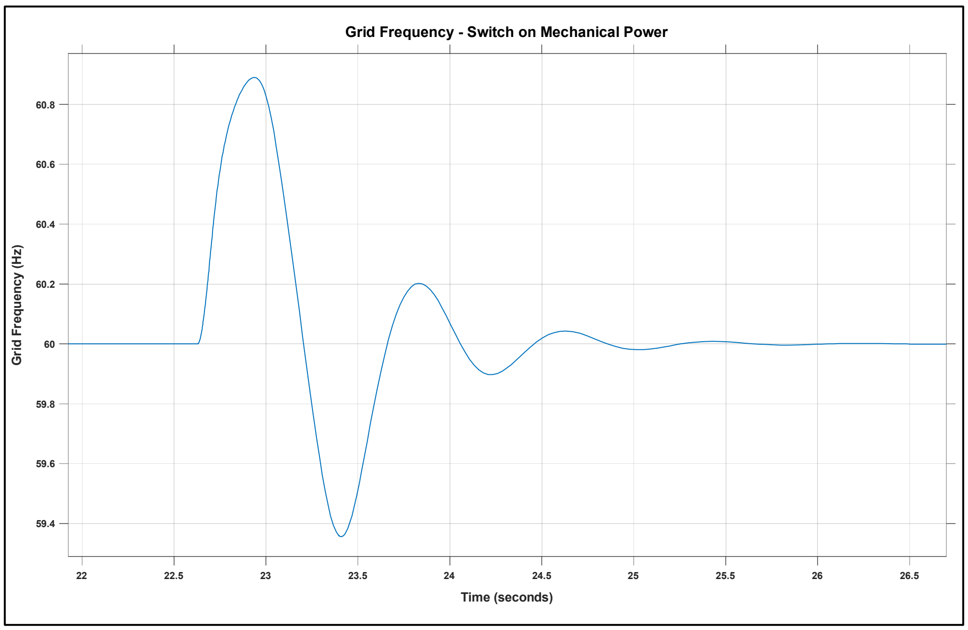

Figure 33: Grid frequency response to instantaneous diesel engine engagement.

The above simulation assessing the clutch engagement response of a DG retrofitted with an SSS-clutch presents valuable insights into the challenges and dynamics of such an operation. The scenario tested, involving a rapid ramp-up to maximum power output, represents one of the most demanding situations for both the generator and engine. The analysis reveals a sharp increase in active power output and a subsequent stabilization period for both active and reactive power. Interestingly, the excitation field voltage response under clutch engagement conditions is more stable compared to disengagement scenarios, with a major spike in field voltage followed by relative stability. The system's rotor speed experiences an initial spike but eventually reaches steady-state operation, thanks to the governor's response in regulating mechanical power input. This simulation highlights the intricate interactions and control mechanisms involved in integrating SSS clutches into DG systems, offering valuable insights for real-world applications and the need for careful engineering considerations to ensure system reliability and stability during rapid engagement scenarios.

5. Conclusion

In conclusion, the comprehensive analysis conducted in this study illuminates the intricate dynamics and trade-offs associated with integrating a SSS clutches into a DG to allow synchronous condensing. More importantly when the integration is in power systems with high Distributed Energy Resource (DER) penetration.

The findings indicate that SCs emerge as promising alternatives to traditional DGs in scenarios characterized by frequent load switching, offering robust performance in terms of ROCOF compliance and voltage correction. SCs' ability to absorb minimal power from the grid and provide current support further underscores their potential as environmentally friendly solutions for modern electricity grids. However, the choice between DGs and SCs is meticulous, as demonstrated by the comparative analysis under fault conditions, revealing distinct advantages and disadvantages for each technology.

Additionally, the investigation into engine engagement highlights the complex control mechanisms required for seamless integration of a SSS clutch into a DG. More research in the control area of this operation should be considered. The investigation into worst case scenario engine engagement illustrates the possible effects the grid may endure and what consequences should be considered.

More research should be conducted in the area regarding the relation of deloading the DG and at what stage the independent shaft speeds of the engine and SM start to differ resulting in SSS-clutch operation. This could serve as a valuable insight into performing a more delicate clutch engagement and disengagement process reducing the overall effects on the isolation system.

Furthermore, there are some potential limitations regarding the simulations performed in this study. The loss of an engine will also reduce the inertia coefficient of the SM. Unfortunately, Simulink states that the SM and diesel engine must have a combined torque coefficient present in the SM block. This particular characteristic limits a more precise simulation of clutch engagement and disengagement process.

Another limitation present is the lack of clutch transition mechanical model. A more appropriate mechanical model to simulate the clutch transition accurately would be more beneficial in determining more accurate results of the effects the transition process has on the excitation system and overall grid characteristics.

Overall, these above insights serve as a valuable resource for power system engineers and planners, emphasizing the importance of tailored solutions and careful consideration when implementing DER technologies in the pursuit of grid resilience and sustainability.

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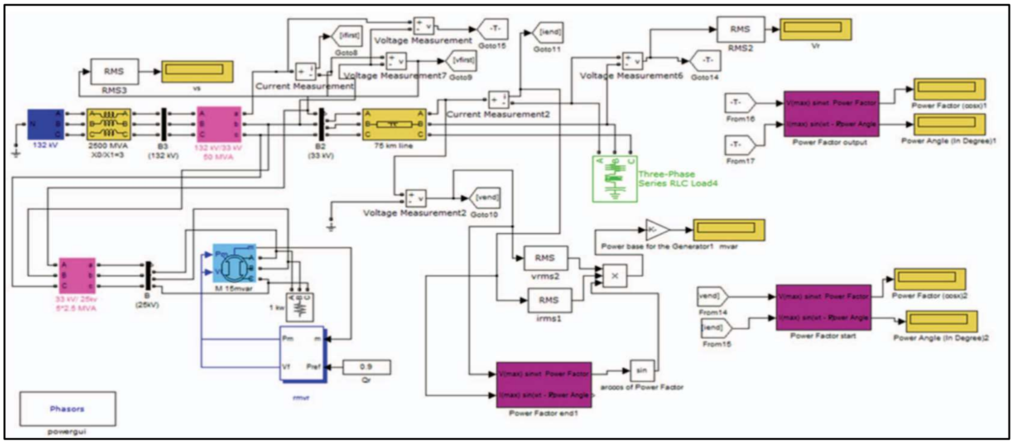
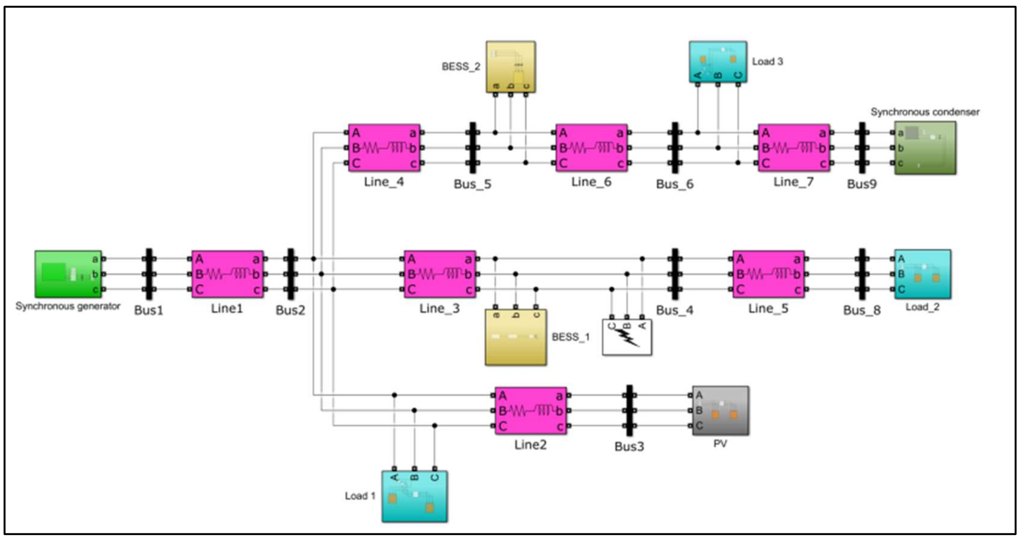
7. Appendix



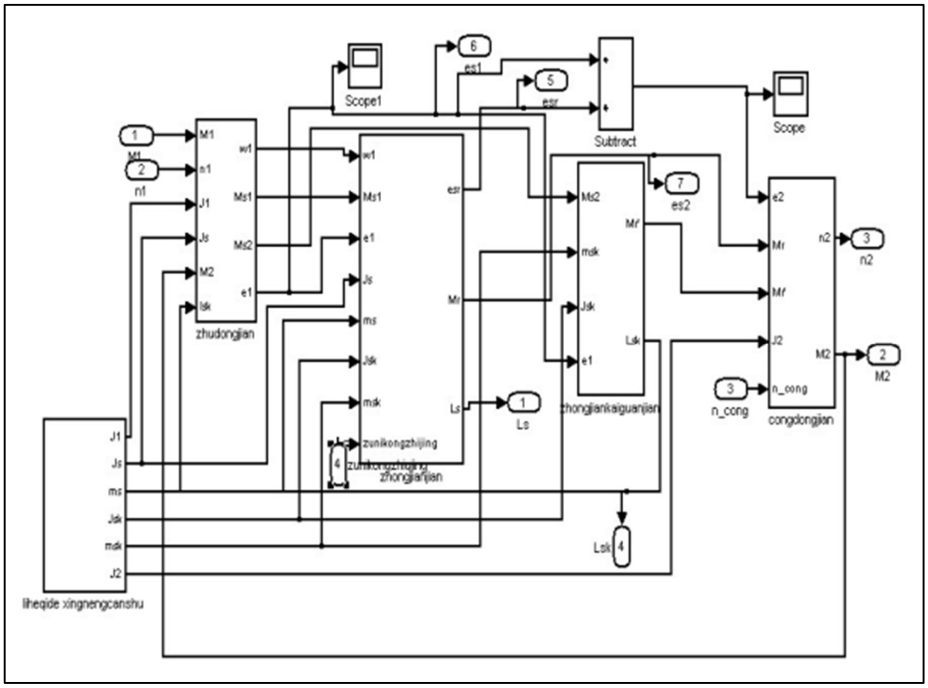
Appendix 1: Simulink Model of SC application in 33Kv MV Network [28].



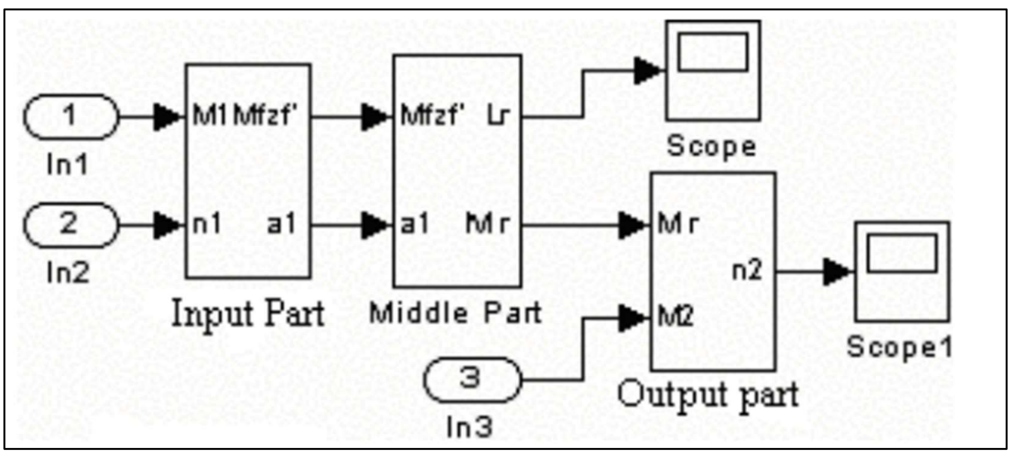
Appendix 2: 20KV Microgrid Model with SC [29].

$$\begin{bmatrix} 1+\dfrac{\tan\beta f_h}{\cos\alpha_h} & 0 & J_{\text{in}} & 0 \\[2ex] 1+\dfrac{\tan\beta f_h}{\cos\alpha_h} & -1 & 0 & -J_s \\[2ex] \dfrac{2(\tan\beta\cos\alpha_h - f)_h}{D_h\cos\alpha_h} & -\left(\dfrac{2f_p}{D_p\cos\alpha_p}+\dfrac{2f_g}{D_g\cos\alpha_g}\right) & -\dfrac{m_s D_h}{2\tan\beta} & \dfrac{m_s D_h}{2\tan\beta} \\[2ex] 0 & 1 & 0 & -\left(J_{\text{out}}+\dfrac{\tilde{J}}{i}\right) \end{bmatrix} \cdot \begin{bmatrix} M_{hr} \\[1ex] M_r \\[1ex] \dfrac{d\omega_{\text{in}}}{dt} \\[2ex] \dfrac{d\omega_s}{dt} \end{bmatrix} = \begin{bmatrix} M_{\text{in}} \\[1ex] 0 \\[1ex] F_R \\[1ex] \dfrac{M_{\text{pro}} - iM_T}{i} \end{bmatrix}.$$

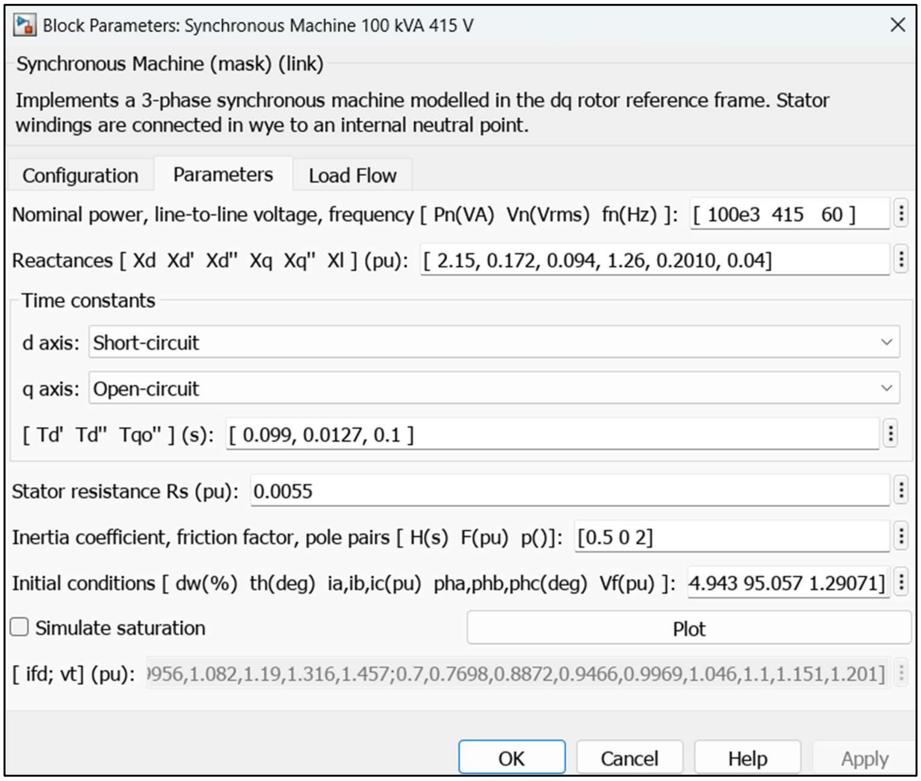
Appendix 3: Matrix form for the kinematics of a SSS clutch engagement [31].



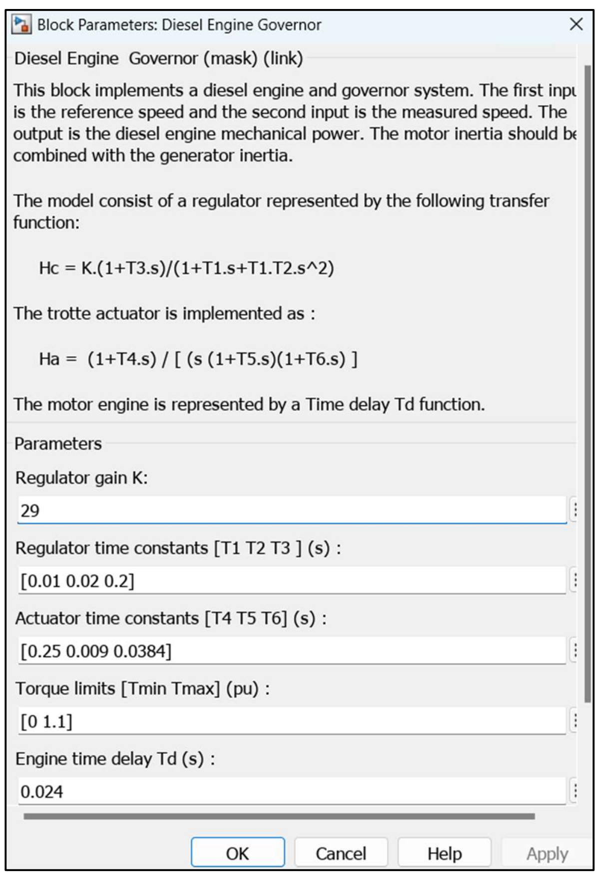
Appendix 4: Simulink Model of SSS clutch engagement process [34].



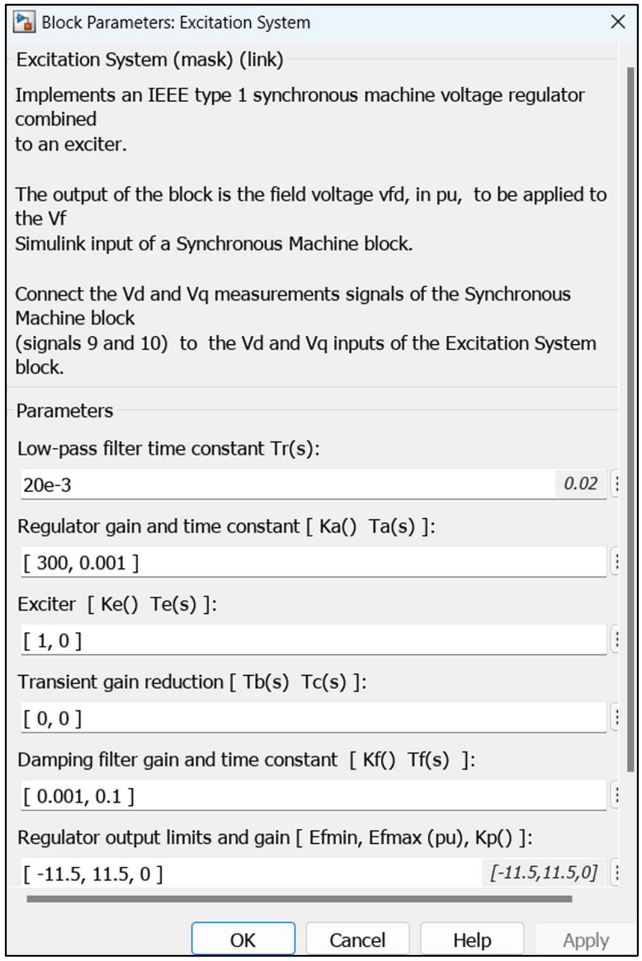
Appendix 5: Simulink model for SSS clutch [33].



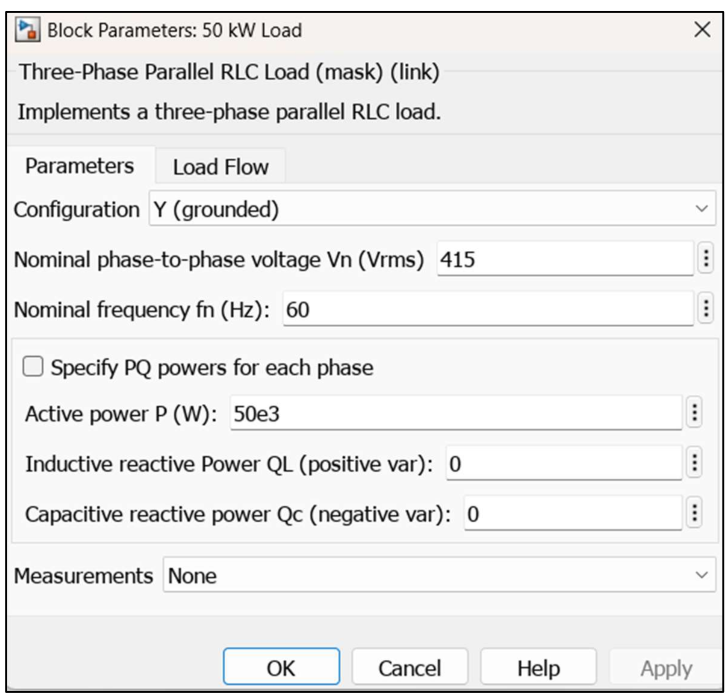
Appendix 6: Final SM block characteristics.



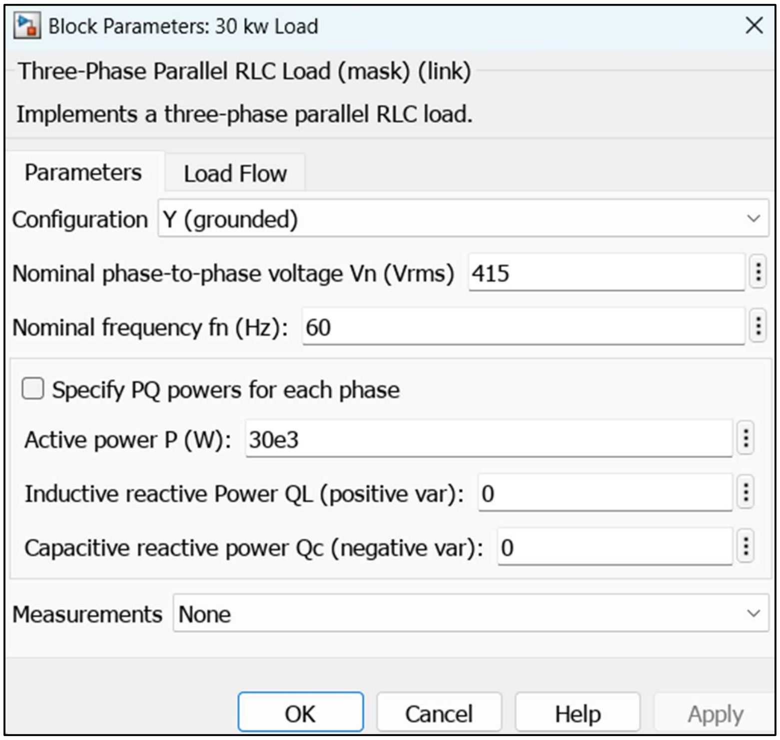
Appendix 7: Diesel engine governor parameters



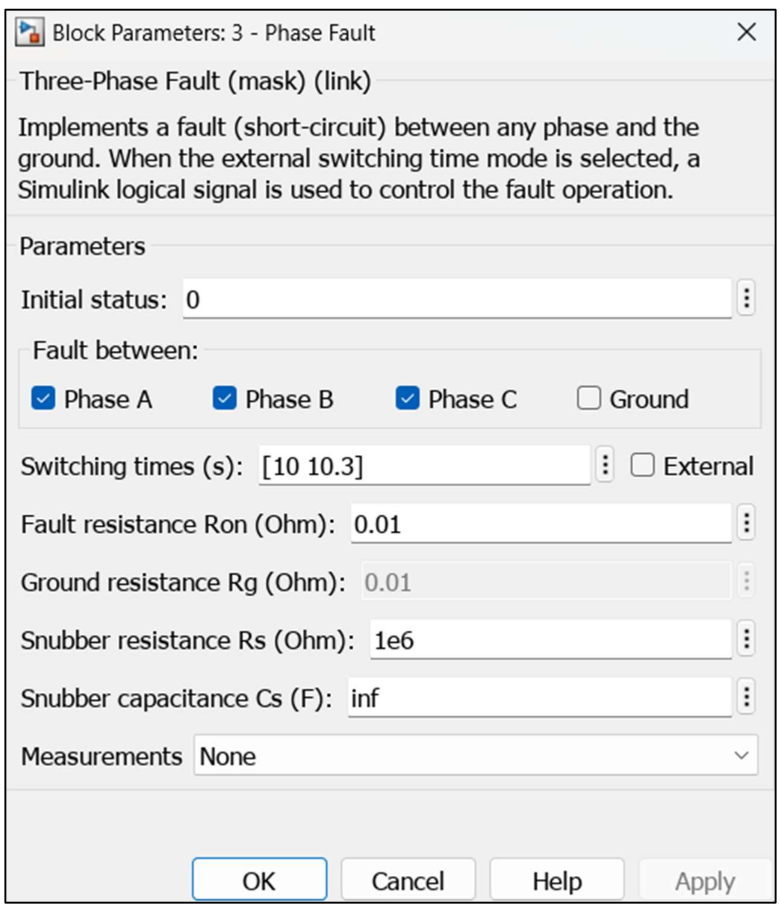
Appendix 8: Excitation System parameters.



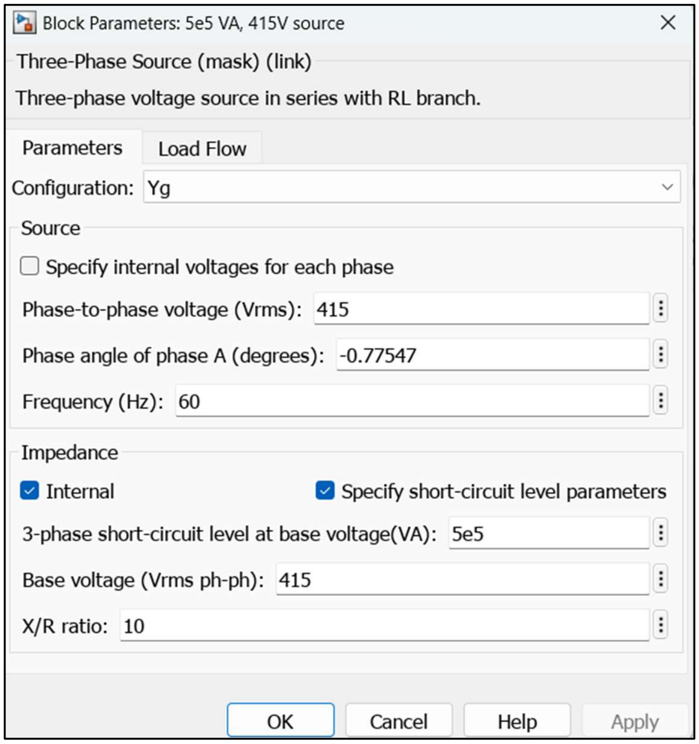
Appendix 9: Constant grid load connection.



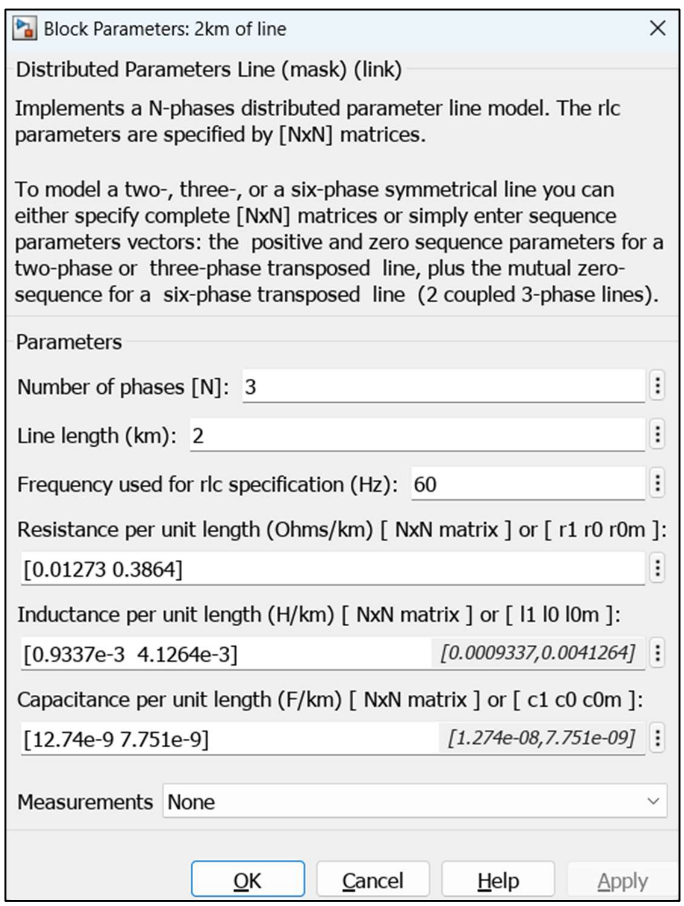
Appendix 10: Load switching grid connection.



Appendix 11: Three Phase fault parameters.



Appendix 12: Grid connection parameters.



Appendix 13: Line impedances parameters.