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An investigation into low-inertia grid stability with high injection of variable renewable energy sources

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Abstract
As the world moves towards decarbonising the energy sector, variable renewable energy sources (VRES) are seen as an integral part of the transition. Much has been researched about the different forms of VRES, which are also known as inverter-based resources (IBR), and of the challenges of integrating them into pre-existing grid infrastructure. Nevertheless, the complex dynamics and impacts on grid stability, particularly within low-inertia grids, are case-specific and so warrant continued attention. This research analyses the specific response of one such grid, on Rakiura Stewart Island of Aotearoa New Zealand, to increasing solar photovoltaic capacity. Issues such as generator motoring and voltage rise are encountered, which suggest that the grid would also see frequency rises. As the capacity of VRES penetration increases, the effects are enhanced. Comparing the results show that negative effects are overall better mitigated by using a decentralised approach, as this offers more even distribution of the generation burden, lower line voltage drops, decreased line losses, and greater line loading reductions. Decentralised systems also have the advantage when it comes to decreasing loading on diesel generators in the grid, reducing fuel use and lengthening the lifespan of the generators. In exchange for these benefits, however, decentralised installations introduce higher node voltages and increase coordination complexity for seamless operation. Subsequent investigations should focus on the strategic integration of energy storage and power electronics, including flexible alternating current transmission system (FACTS) devices and static synchronous compensators (STATCOMs).
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Keywords: Grid stability; Inverter-based resources; Low-inertia grid; Power quality.

1. Introduction
The world has crossed into an important threshold in the climate crisis, having exceeded a 1.5°C rise in temperature (McCulloch et al., 2024). The potential effects of this increase are devastating, with loss of biodiversity, changes to ocean chemistry, increased frequency and magnitude of droughts, and increased risk of water scarcity (IPCC, 2022). It is imperative that every effort be made to prevent the Global Mean Surface Temperature (GMST) from rising above 1.5°C to stave off more intense impacts.

Net greenhouse gas (GHG) emissions have increased since 2010 across all major sectors. In 2019, approximately 34% (20Gt CO_2-eq) of net global GHG emissions came from the energy sector (Calvin et al., 2023). It is obvious that work must be done towards making this sector more sustainable; electricity is a necessity in modern existence, and its production must become cleaner. Grids are traditionally comprised of steady and predictable sources of fossil-fuelled power, but the most accessible and popular forms of renewable energy are intermittent and varying. After many years of inaction, the grid suddenly finds itself inundated with more of these intermittent sources. There is no turning back, as the number of installations is expected to accelerate. The International Energy Agency (IEA, 2023), in a net zero emissions scenario, sees renewable energy sources accounting for over 60% of the generation mix, with wind and solar together accounting for approximately 40% of the mix.

On average, most wind installations are utility-scale, but solar photovoltaic (PV) installations often find themselves in the hands of the end user. High retail electricity prices and government support for low-cost incentives act as drivers for adoption at the distribution level. The IEA (2023) forecasts over 1 TW of distributed solar PV between 2023 and 2028.

This added capacity is second only to utility-scaled PV and far outstrips all the other RES technologies. The logical conclusion is that the grid has no choice but to adapt to this new, and projected majority, energy source. This necessary adaptation is particularly problematic for low-inertia grids. Inertia is the tendency of an object in motion to remain in motion. The National Renewable Energy Laboratory (NREL) defines grid inertia as the kinetic energy stored in spinning generators (Denholm et al., 2020). Grid inertia is derived from many generators that are synchronised, rotating at the same frequency. Low-inertia grids are therefore either grids that have low overall nameplate capacity installed, for example on small islands, or grids that see high amounts of variable renewable energy sources (VRES) replacing conventional generation systems. It is a measure of how capable the grid is to ride through disturbances, or, more simply, grid instability. In these low-inertia grids, the myriad negative effects of high VRES injection can be more impactful. The intermittency of VRES can result in discrepancy between load and demand, potentially leading to grid instability, and even blackouts (Kumar et al., 2025). Grid stability can generally be classified into voltage stability, frequency stability, and rotor angle stability. The latter two are outside the scope of this paper, but voltage stability is defined as the ability of a system to maintain voltage within a certain limit for a specific time, and maintain a steady-state voltage profile after disturbances (Al Kez et al., 2020).
As grid stability and reliability are pivotal for ensuring that consumers have uninterrupted power (Ishraque et al., 2021), it is imperative that the effects be addressed and solutions be developed. Currently, placing intermittent RES on grids can cause several problems. Ayadi et al. (2020) mention that the challenges of integrating renewable energy sources into the grid include, but are not limited to, power quality and variation of power generation and its speed.

Power quality is affected by multiple parameters, including:

- Voltage fluctuations can be sags (temporary reduction in voltage) or surges (temporary increase in voltage). Brinkel et al. (2020) state that the main power quality problems associated with rapid PV output fluctuations are voltage fluctuations and light flicker, which is induced by the voltage fluctuations. Voltage fluctuations and flicker can cause damage to electrical appliances connected to the grid and light flicker can cause annoyance and health problems to people exposed to it (Brinkel et al., 2020).
- Frequency variation occurs when the frequency deviates from the standard frequency (50Hz or 60Hz). This variation can disrupt the operation of some very time sensitive equipment. Al Kez et al. (2020) state that lower system inertia can result in deeper frequency excursions and higher rate of change of frequency (RoCoF) with fragile dynamic responses. They explain that this is due to renewable energy technologies being typically decoupled from the grid by power electronic converters that limit their natural response to frequency variations. As system inertia is critical to reducing RoCoF and counterbalancing the frequency recovery to the pre-event value, large system RoCoF may result in tripping, customer load shedding and eventually, a blackout.
- Power factor is essentially a measure of how effectively electrical power is converted into useful work output. Global Sustainable Energy Solutions (GSES,

2016) explains that power factor is the phase difference between the voltage and current in an AC power system. A non-unity power factor means that a load is consuming both active power and reactive power. Active, or real, power is the 'useful' component of AC power and is responsible for work done in a system. Reactive power does no work but is needed to maintain the voltage in the system by facilitating the transmission of active power through the network. According to GSES (2016), most grid-connected PV inverters are set up to inject power at unity power factor. This means they only produce active power. This would reduce the power factor, as the grid is then supplying less active power, but the same amount of reactive power. A lower power factor can result in wasted energy.

In addition to power quality issues, renewable energy sources are mainly intermittent and so cannot guarantee constant and stable production. Another concern is that they may not be able to produce the amount of power needed at the required rate. Moreover, high penetration of renewable generation can have implications for line and transformer loading, as well as associated losses.

As previously mentioned, the problems faced are more amplified on smaller grids. Due to their size, they tend to have low nameplate capacity, which translates to reduced inertia. This poses significant difficulties for small islands where low-inertia grids are common. Nevertheless, lessons learned here are not just for small islands but can be modified for application in context to any nano- or microgrid amid much larger grids.

1.1. Objective of the paper

This paper investigates how a small grid could be affected by adding solar PV and other inverter-based resources. In particular, the research considered the types of instability that can occur in a low-inertia grid as VRES are added, to answer the following questions:

- What power quality factors such as voltage fluctuations and frequency variations will arise? Would there be any issues with the transmission lines and transformers?
- How do low-inertia grids respond as more VRES with IBRs are installed?
- Does it have the same response if the VRES are centralized versus decentralized?.

2. Literature review

The purpose of the literature review is to ascertain what areas of grid-integration of VRES have received the most attention in recent years, with an emphasis on the technical effects of VRES on the grid, and strategies to overcome barriers. In particular, the review investigates three main questions:

- How do low-inertia grids perform with increasing penetration of VRES?
- What is their limit of VRES penetration compared to their size?
- What are the most effective technologies to mitigate grid-stability challenges associated with increased VRES penetration?

2.1. Review approach

To determine what is deemed as important to researchers concerning the integration of VRES into grids, a narrative literature review was undertaken. Narrative reviews allow for the inclusion of a wide variety of studies and provide an overall summary. They are useful for generating new ways of thinking in areas that are well researched, or for gaining new insights (Sukhera, 2022). The review focussed on grid integration from the vantage point of physical implementation and the effects. No consideration was given to policy implementation, socio-economic factors or the monumentality of implementation. The review process consisted of utilizing several academic search engines. Search terms and keywords were defined for the query. The literature was restricted to those published from 2017 onward.

After gathering the pool of literature, they were more carefully assessed for relevance by going through the abstracts. Papers that were irrelevant were discarded. The remainder were then thoroughly assessed for content. It was noted what themes and approaches were recurring. At the end, thoughts were given on the different areas that require investigating when it comes to successfully integrating VRES into existing grids.

2.2. Review outcome

Twenty-four papers were finally included in the review.

2.2.1. Temporal focus shifts

The earliest paper of Kroposki et al. (2017) focussed on the feasibility of a 100% renewable grid. It is essentially a review, highlighting the challenges of high variable renewable energy grid penetration and the need for the grid to become flexible. It then suggests a few strategies for adoption and protection. By 2019, authors were more keyed in on the specifics of where the grid is most vulnerable, with Johnson et al. (2019) concluding that rotational inertia is a key factor in grid reliability. Storage is also discussed more explicitly, with Zsiborács et al. (2019) pointing out the critical role of energy storage systems in balancing supply and demand. The paper specifically modelled energy storage requirements for the European grid for high variable renewable energy penetration. This marks a shift from thinking about the issues abstractly, to actively looking into technical requirements. As the years progress, more attention was given to storage and the role storage plays in grid reliability. Dowling et al., (2020) posits that long-duration storage is a method to significantly enhance grid reliability by smoothing out fluctuations. By 2021, there was focus on other methods for facilitating grid reliability. Adetokun and Muriithi (2021) review fast AC transmission systems (FACTS), the types and their applications, especially in grids with high levels of renewable energy integration. There was also focus on optimization of smart grids, with Yaghoubi-Nia et al. (2021) tackling an optimal stochastic method for allocation of protective devices and distributed generation of smart grids. Kim et al. (2020) used Monte Carlo simulations, Weibull distributions, and enhanced spatial modelling based on universal kriging to create probabilistic models to estimate wind energy potential for power grid expansion planning. In the most recent years, there is focus on hybrid approaches, with Maghami et al. (2024) declaring that there is no one size fits all solution, and advocate for a mix of both energy storage and demand response.

2.2.2. Island-specific studies

Meschede et al. (2022) performed a review on scientific literature that focussed on 100% renewable energy systems on islands. Figure 1 shows the distribution of the reviewed literature across the categories, as well as the historical development of the literature. It is observed that the idea of a 100% RES transition on islands really take off circa 2018.

The results show that most of the literature reviewed focussed on assessing a 100% RE scenario, assessing technology, then assessment of renewable energy systems, in that order. In looking at the scenarios, the authors of those papers considered supply and demand. Bertheau and Cader (2019), Ma et al. (2015) and Yoo et al. (2014) all looked at increasing renewable energy penetration from a levelized cost of electricity (LCOE) perspective. Storage was looked at as load fulfilment, not as a tool for grid stability.

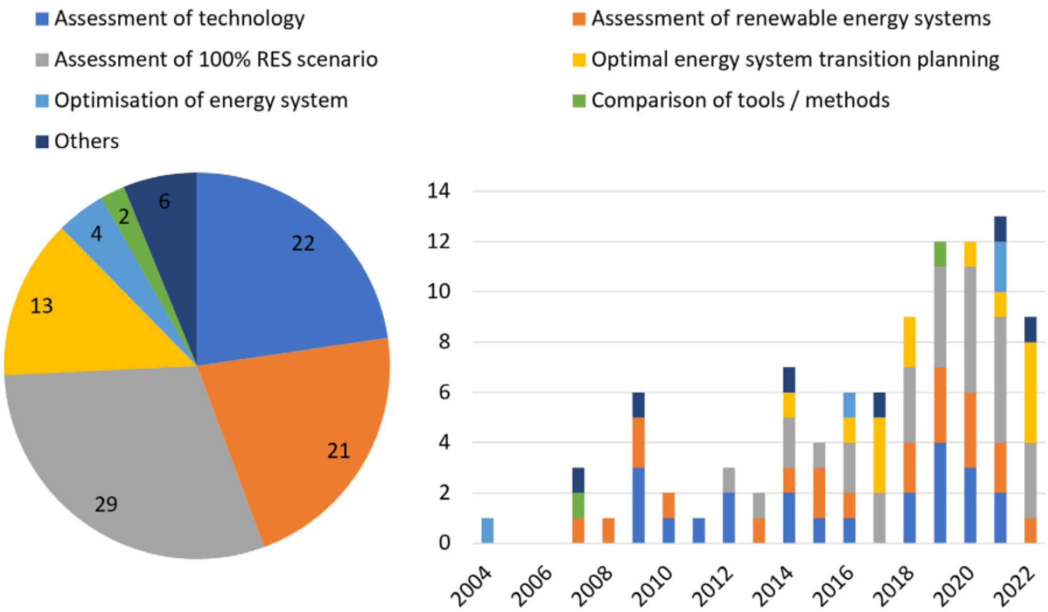

Figure 1. Purposes of the reviewed studies
(Source: Meschede et al., 2022)

One review (Chen et al., 2020) looked at possible pathways to 100% renewable energy in Jamaica. It was the only paper in the review of Meschede et al. (2022) that specifically looked at the transition while considering grid stability. The grid was identified as one of low-inertia and there was empirical evidence of the issues that arise with increasing variable renewable energy sources. As such, this paper looked at battery storage as a method of control and then did an economic analysis based on that scenario. It was noted that system stability is most important, and inertia can be delivered as synthetic inertia from batteries (Hodge et al., 2020). It was suggested that isolated power systems on islands can be seen as testbeds for fully inverter-based power systems.

2.3. Review discussion

The literature reviewed showed that grid stability is seen as important, as the number of variable renewable energy sources on grids continue to grow. Storage was the focus of 29% of the papers, highlighting its perceived importance to the ability to successfully transition. In contrast, the power grid is the focus in only 16% of the papers. However, in recent years the importance of maintaining grid stability with greater injections, of what Hodge et al. (2020) refer to as Variable Inverter-Based Renewable Energy Sources (VIBRES), is coming more to the forefront, although methods proposed are largely speculative or context specific. Recently, much effort is being diverted to the response of the grid via other methods such as FACTS, smart-grip optimization, and demand-side management.

Several studies explicitly identified the vulnerability of low-inertia grids, noting that system reliability declines with rising VRES penetration. However, the available literature does not delve into the actual performance of low-inertia systems under varying levels of VRES penetration. Therefore, while it is accepted that these systems face significant challenges, there is limited comparative analysis of their performance.

Few studies establish clear VRES penetration thresholds relative to grid size. Research geared towards islands and microgrids are generally approached from techno-economic or cost perspectives, rather than operational stability limits. This represents a notable research gap.

In contrast, mitigation technologies are more thoroughly explored. Recent studies agree that there is no single technology that can fully address stability challenges; context-specific combinations are required. The literature underscores the urgency of developing tailored approaches for low-inertia grids but does not address their performance limits with high VRES penetration.

What is glaringly lacking from the literature is research directed towards stand-alone microgrids, particularly those grids of small islands, and where their limits for renewable energy penetration are. Continuing along that line, there is little research on how these specific microgrids can be made flexible and reliable. This presents excellent research opportunities for creating models and case studies, as there are many islands with their own unique situations that are looking to increase their renewable energy uptake.

3. Research methods

The research revolved around modelling the grid of Rakiura Stewart Island, Aotearoa New Zealand's third largest island (see Figure 2). There are approximately 450 permanent connections on the distribution network, and it is serviced by five diesel generators (four in-service and one backup) located in a central power station (Southland District Council, 2023). The grid used in this project is intended to be as realistic as possible. To ensure this, the following data were collected from the Stewart Island Electricity Supply Authority (SIESA) to create a base case:

- The capacity and location of existing generators;
- Node connections and locations;
- Transformer ratings and other parameters;
- Base voltage level;
- Frequency; and
- Load profiles.

Figure 2. Location and map of Rakiura Stewart Island

The PowerFactory software of DIgSILENT was used to model the grid and carry out the simulations. PowerFactory is a leading power system analysis software application for use in analysing generation, transmission, distribution and industrial systems. Relevant features for this research include:

- Models of generators, governors (steam, gas, diesel, hydro), automatic voltage regulators (AVRs) and power system stabilisers (PSS);
- Economic assessment using the Power Park Energy Analysis tool;
- Steady-state load flow calculations taking into account voltage-dependent reactive power capability limits, power park controllers with set-point characteristics, and so forth;
- PV system model with integrated power calculation based on solar radiation (1 and 3-phase technology);
- Medium- to long-term Quasi-Dynamic simulation;
- Dynamic models according to IEC 61400-27-1 and WECC
- User-defined modelling for Quasi-Dynamic, RMS and EMT simulation; and
- Power quality assessment including harmonic analysis with frequency-dependent Norton equivalents, impedance frequency sweeps and Flicker meter calculation.

Given its expansive list of capabilities, it was seen as the optimum choice for modelling the grid for this research.

Rakiura Stewart Island has two feeders. Feeder one was modelled in detail while Feeder two was abstracted. This approach was adopted to reduce computational burden, as detailed modelling of Feeder One yielded sufficient insight to validate system behaviour and ensure model fidelity. Feeder Two was retained in the model in an abstracted form to preserve network topology and boundary conditions. The modelling entailed:

- Modelling line lengths, types, material and locations;
- Ensuring the transformer parameters and locations match current real world;
- Using the load profiles provided by the utility; and
- As accurate as reasonably possible provide representations of node connections.

The load information received from SIESA consisted of the total load for each feeder in ten-minute blocks. The load information for every hour was extracted to create a one-year load profile. Feeder 1 has 16 pole-mounted transformers of capacities ranging from 5kVA to 100kVA. The load for each time segment was proportionally allocated to each transformer. The location of each transformer, as well as the power plant, was verified using Google Maps Street View for the island. Feeder 2 was abstracted to a single node of considerable distance from the power plant through which its total load was applied.

The power plant consisted of four generators. The backup generator was excluded as it was considered superfluous. Two were rated at 440kW, while the remaining two were 380kW and 300kW. They are serviced by two station transformers that step up the voltage from 415V to 11kV for transmission around the island. The pole-mounted transformers step the voltage back down to 415V for distribution to buildings. The specifications of the pole-mounted and station transformers were not received from SIESA, so they were modelled after typical ETEL branded transformers that are used in Aotearoa New Zealand using the capacities stated on the single line diagram.

Line lengths, types, and the locations of the pole-mounted transformers were also not received from SIESA. The locations of the transformers were obtained by referencing the single line diagram and ‘roaming’ the feeder in Google Maps Street View until transformers were found. The location of the power plant was also verified using Google

Maps and cross-referencing with Open Maps. All locations were recorded. Once the locations were input into PowerFactory, the line lengths between objects were automatically calculated. For line type, a visual inspection of the lines in Google Earth Street View showed bare conductors. Using an advanced image recognition system, it was determined that the lines were likely Aluminium Conductor Steel Reinforced cable (ACSR) of between 10mm and 12mm. Looking into standards, they were modelled as 'Dog' which fits the determined size and is typically used in Aotearoa New Zealand in this setting.

All investigative changes were done on the detailed feeders, and the behaviour of the overall system observed. The investigative method was as follows:

- The base case grid was designed, and its behaviour modelled.
- Operational scenarios for solar PV penetration were implemented in increments of 50kW.
- As the PV is being injected into the grid, records would be kept of the grid's response.

Two permutations besides the base case were modelled:

- Centralised solar PV; and
- Decentralised solar PV.

With each permutation:

- Power flow studies were carried out to see how the flows changed as more solar PV is injected into the grid;
- Voltage stability was assessed with the incremental increase of solar PV; and
- Change in grid losses with increasing solar PV was investigated.

3.1. Simulation

Buses are nodes where one or more components (generators, loads, transformers, and so forth) are connected. There are three types, but of great importance to carrying out a successful simulation in PowerFactory is the Slack (SL) Bus. This is also known as the Swing Bus or Reference Bus, and is designed to balance the active and reactive power in the system due to system losses and inaccuracies in demand forecasting. The slack bus provides the reference for the phase angles and absorbs the discrepancy in power flow calculations, adjusting to balance load and generation across the system. Total generation should be equal to (total load + transmission losses). However, these losses cannot be directly calculated until the load flow is solved. The SL bus provides the necessary balance by adjusting its real power to match system losses. There is one SL bus in a system, and it is often linked to the main control point of a large utility.

For Rakiura Stewart Island, there is one power plant that houses the generators. Consequently, the bus that the generators are connected to is the only one that can be designated as the SL bus. Generator G2 (440kW) was designated as the reference machine. This means that the generator is configured as slack. The implications of this are that the voltage angle of whatever terminal the generator is attached to is fixed, and that balances active power if the Active Power Control option as Dispatched is selected and the Balancing option by Reference Machine is enabled. Generator G2 therefore sets the SL bus voltage angle, but as all four generators are connected to the same terminal, balancing is done by distributing slack among the generators. The remaining three generators were set to a Q(P) characteristic as they cannot all control the SL bus voltage. This is a reactive power controller that adapts the setpoint according to the active power output of the machine.

The characteristic that was set declares that at low loads, the generators inject some reactive power. At medium loads, the generators are neutral. At high loads, the generators absorb some reactive power.

A Quasi Dynamic Simulation was run for the year to establish the baseline values for the following parameters:

- Line voltage drop (%);
- Line losses (kW);
- Line loading (%);
- Terminal voltages (per unit);
- Generator active power (kW); and
- Transformer loading (%).

A new study case was created for adding centralised PV systems. Here, all the PV systems were installed in one location. The lot that holds the power plant was assumed for the installation. A PV system size 25kW was installed, then increased to 50kW. Installations then increased in 50kW increments up to 250kW. In each case, a Quasi-Dynamic simulation was run for two years, with the values for the aforementioned parameters recorded. Added to the list was the PV system output.

For the study case of decentralised PV systems, the same size systems were used but divided among the different load points. The total PV capacity was proportionally allocated by feeder size based on total load usage. The annual load usage for feeders 1 and 2 was tallied and added together to get the total load for the grid. Then the feeders were allocated a portion of the total PV system using the formula:

$$F_X allocation = \frac{F_X load}{Total\ load} \quad (1)$$

The allocation for feeder 1 was then divided equally amongst the 16 transformers.

The solar panel used in the simulation was the Trinasolar TSM-NE09RH.05 445W, which sports 22.3% efficiency, and the inverter efficiency was set at 98%.

Plots were generated for all the parameters checked, as visual indicators of the result. The data was exported to CSV files for further analysis.

3.2. Assumptions and considerations

- The static load flow model was not validated against real word measurements, only assessed for reasonableness.
- The research project was not meant to be a feasibility study on transitioning to renewable energy sources, and it is therefore assumed that the solar PV potential, or any variable renewable energy sources used, is present.
- Solar PV was installed at optimum tilt angle and azimuth.
- The solar PV panels used are commercially available.
- Storage would be in the form of batteries, and would be commercially available.
- The built-in capability of PowerFactory would be used for building the irradiance and temperature profiles of the locations.

- Though Rakiura Stewart Island is being used as the model for the grid, the results are not exclusive to the grid of Rakiura Stewart Island. The trends seen can be expected in grids in different locations.

4. Results and discussion

4.1. System modelling results

The results of the quasi-dynamic simulation in the base case are what the centralised and decentralised PV system results are compared to, and the maximum values are summarised in Table 1.

Table 1. Results of parameters in the base case

Parameter	Value
Transformer Loading	~65%
Transformer Losses	11.4kW
Line Loading	2.43%
Line Losses	1.68kW
Terminal Voltage	~0.99

4.2. PV installation results

4.2.1. Terminal voltages

Like everything else in power distribution, voltages are kept in a strict range. This is generally 0.95 p.u. to 1.05 p.u. For both the centralised and decentralised systems, there was voltage increase with the installation of the PV systems. The voltage increases corresponded with the output with the PV systems, with the winter period seeing lower voltage increases. The voltage changes also increased with increasing size in the PV installation capacity. Decentralised PV systems saw higher voltage increases compared to centralised PV systems (see Figure 3). This is especially true at the higher PV capacities.

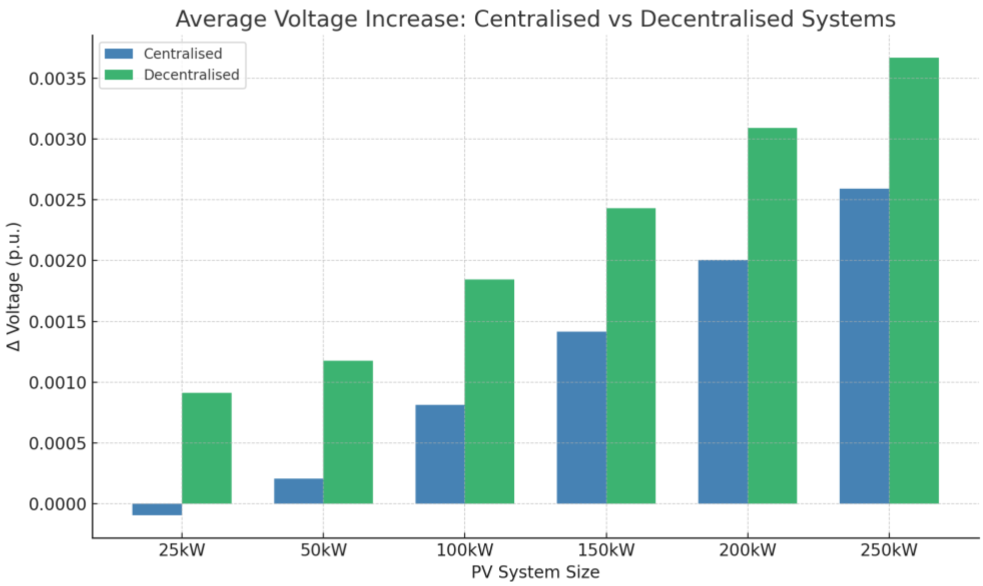

Figure 3. Average change in voltage comparison for centralised and decentralised PV systems

4.2.2. Line voltage drop

Line voltage drop refers to a reduction in voltage as electricity travels through the conductor (line) from the power source to the load. The drop is caused by the internal resistance and reactance of the conductor, and leads to some of the generated electrical energy to be lost as heat and reactive power. Voltage drop is also influenced by:

- The length of the line, where longer distances mean increased resistance and reactance;
- The current flowing through the conductor, where higher current means a greater voltage drop; and
- The power factor, where a poor power factor increases apparent power and leads to higher voltage drops.

The installation of PV systems decreased the voltage drop for most lines in both centralised and decentralised installations (see Figures 4 and 5).

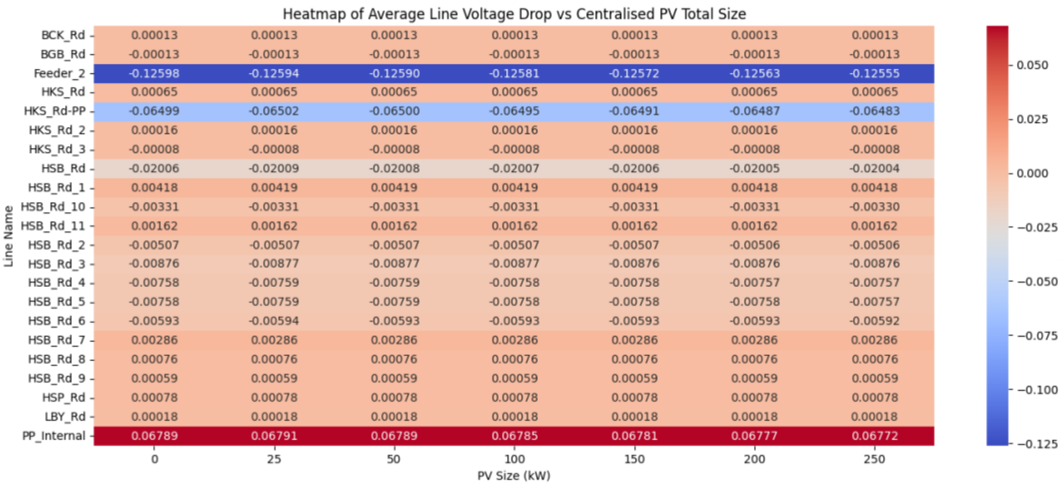

Figure 4. The effect of centralised PV systems on line-voltage drop

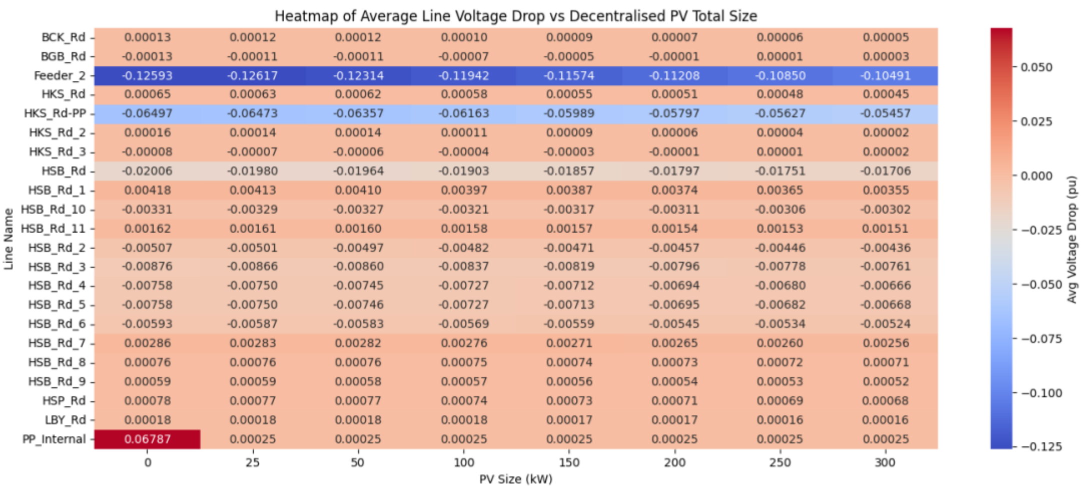

Figure 5. The effect of decentralised PV systems on line-voltage drop

For centralised systems, that decrease can be explained by the drop in current from the generators as the PV supplies part of the demand to the load. Decentralised systems produce the greatest reduction in voltage drop. Feeder_2 sees the greatest improvement at the highest installation capacity of a decentralised PV system. This is because the PV system is installed at the point where the load is utilised, and the generated power therefore doesn't have to travel very far. The Feeder_2 node is furthest geographically from the power plant than any other node, so a centralised system installed at that location would not improve conditions along the Feeder_2 line. Conversely, the PP_Internal line comes under the most stress for the centralised PV systems. This is because line PP_Internal is the line that feeds all power generated out to the entire grid.

4.2.3. Line loading (%)

Line loading is defined as the amount of current-carrying capacity a line is using. In other words, it shows how heavily a line is used. Lines that are overloaded are at risk of overheating, so it's important to make sure the capacity is within tolerance.

The results showed that as the capacity of the centralised PV system increases, the average line loading decreases (see Figure 6). PP_Internal, the line from the power station that distributes to the rest of the grid, and HKS_Rd-PP, see marked reduction as compared to other lines. Some lines do see a slight increase in loading with smaller PV system sizes. Lines further from the installation require a higher capacity installation before a reduction in loadings is seen.

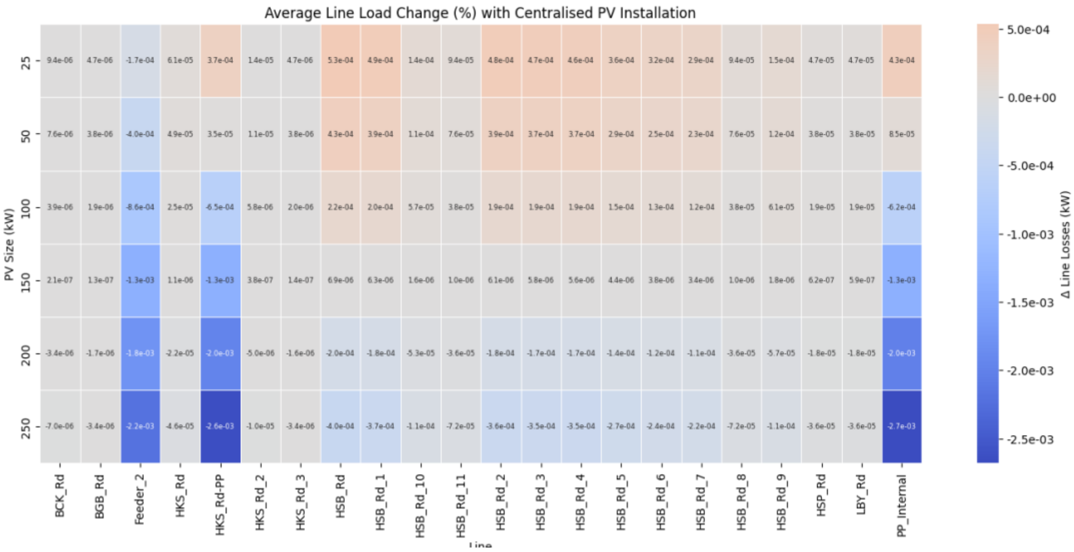

Figure 6. The effect of centralised PV systems on line loading (%)

With decentralised PV systems however, there is a much greater reduction in line loading (see Figure 7). The reduction is seen in even lower capacity PV installations. This makes decentralised PV systems a better option for reducing line loading. Line PP_Internal benefits the most here, as it is much further away from the power plant. With a PV system on site, there is less distance for the electrical power to travel.

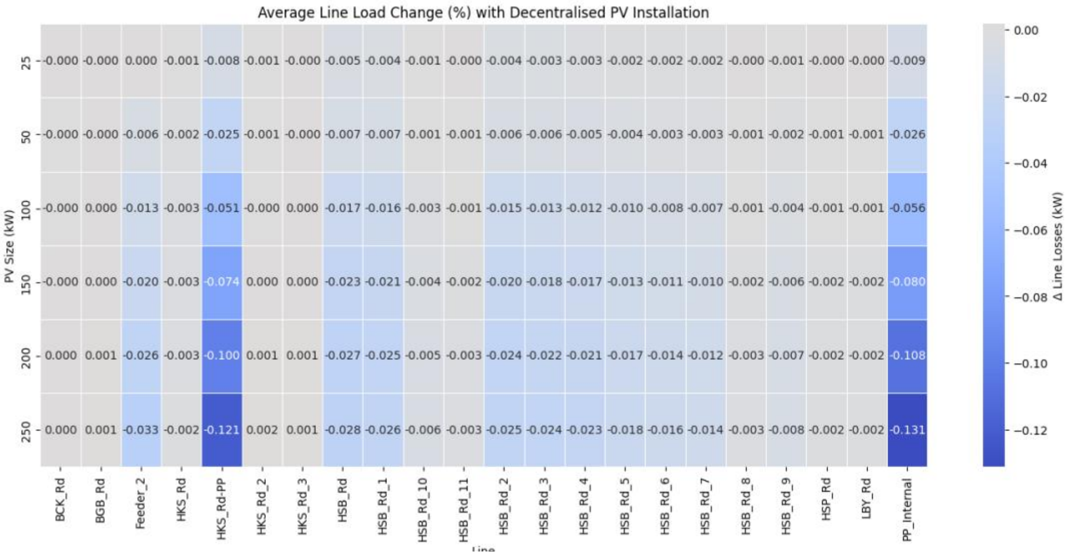

Figure 7. The effect of decentralised PV systems on line loading (%)

4.2.4. Line losses

Line losses in power lines are electrical energy lost as heat due to the internal resistance of the line conductors when current flows through them. As line losses are proportional to I2R, higher current or longer distances increase losses.

Increasing the installed capacity in a centralised PV system does not affect line losses (see Figure 8). With a decentralised PV system however, line losses decrease as PV capacity increases. This is especially true with long lines such as Feeder_2.

4.2.5. Transformer loading (%)

In the same vein as line loading, transformer loading is a measure of how much of a transformer's rated capacity is in use. Knowing the transformer loading aids in keeping them from overloading and being able to plan their lifespan, as well as ensuring they are properly sized for the power flow in the area it is installed in.

The centralised PV system has a negligible effect on transformers away from the installation regardless of the size of the installation (see Figure 9). On the contrary, transformer PV_Tx, which is the transformer that services the centralised PV system, sees an increase in loading % as the system size increases. The situation is different with decentralised PV systems, however. Increases in PV capacity resulted in increases in transformer loading. The increase is inversely related to the rated capacity of the transformer. Feeder 2's total load profile is approximately 1.6 times that of Feeder 1. Feeder 2, as a result, when receiving its allocation of the decentralised PV system, had PV systems sizes far greater than Feeder 1. This drives the increase in transformer loading with the PV system size. The remaining transformers see increases according to their rated capacities. Transformer 18 being only a 5kVA would see the greatest increase in loading with increased PV installation. As the transformers increase in size, they have more capacity for the same increase in PV size as transformer 18.

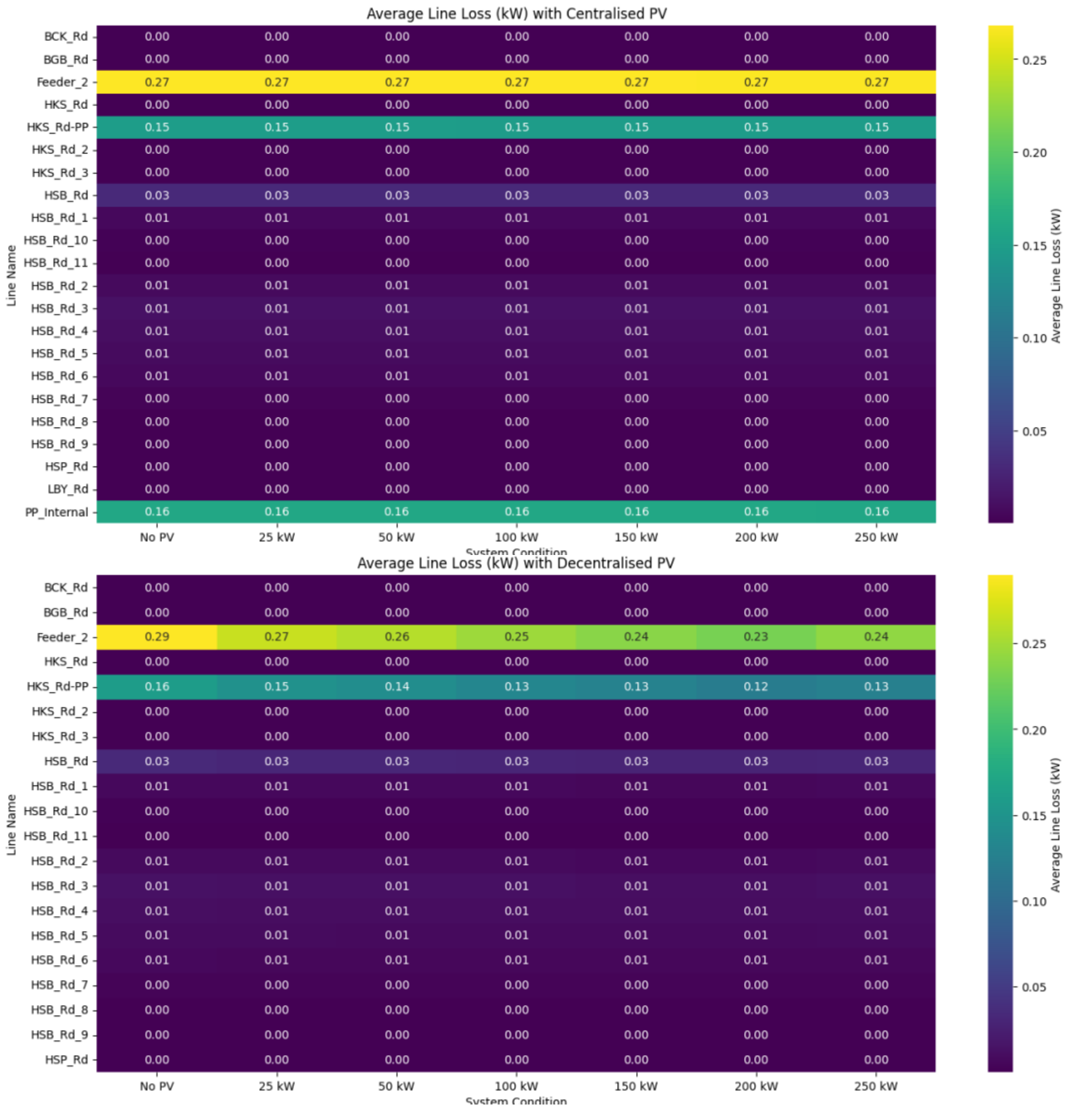

Figure 8. Effect of centralised (top) and decentralised (bottom) PV systems on line losses (kW)

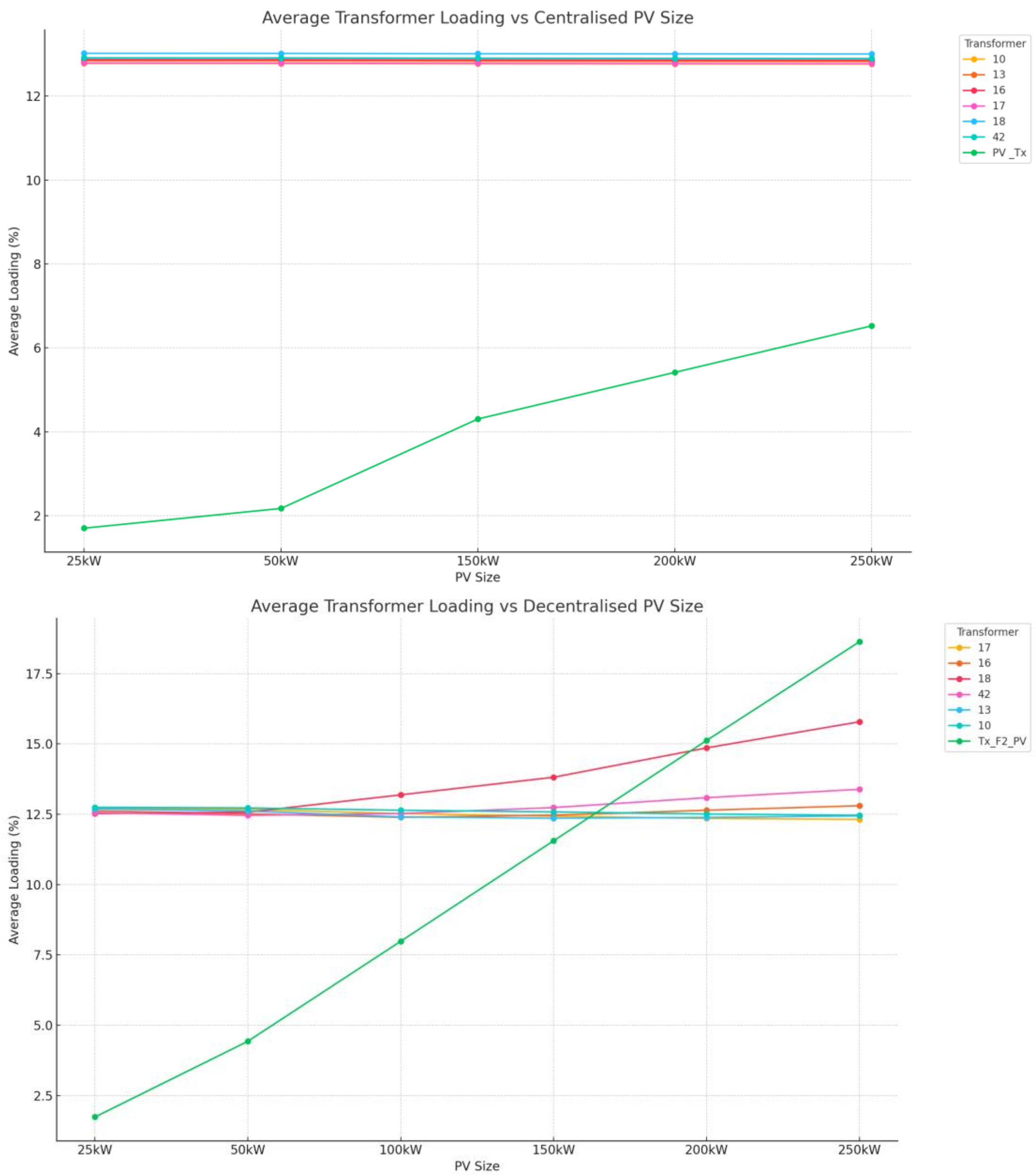

Figure 9. Effect of centralised (top) and decentralised (bottom) PV systems on transformer loading (%)

4.2.6. Generator loading

Generator loading % is a ration of the generator's apparent power (S) output to its rated capacity. It is an indicator of the operational efficiency of the generator. The generator load percentage was calculated as follows:

$$Generator\ Load\ \% = \frac{S = \sqrt{(P^2 + Q^2)}}{Nominal\ Rating} \times 100] \qquad (2)$$

The generator loading was calculated for the week of 18 to 25 November in scenarios without PV and with 250kW installed. Both the centralised and decentralised installations were investigated. This week was chosen as it exhibited high voltage rise when PV was installed. The objective was to determine the effect, if any, that installing PV on the grid would have on the generator usage.

Both types of PV systems decreased generator loading, though the decentralised systems resulted in lower generator loading, particularly during the daytime (see Figure 10). This is explained by decentralised PV reducing local demand more effectively. There are some minute differences in the performance of generators G1, G3 and G4. Generator G2 is the reference machine, and therefore transitions into a reactive sink during PV peaks.

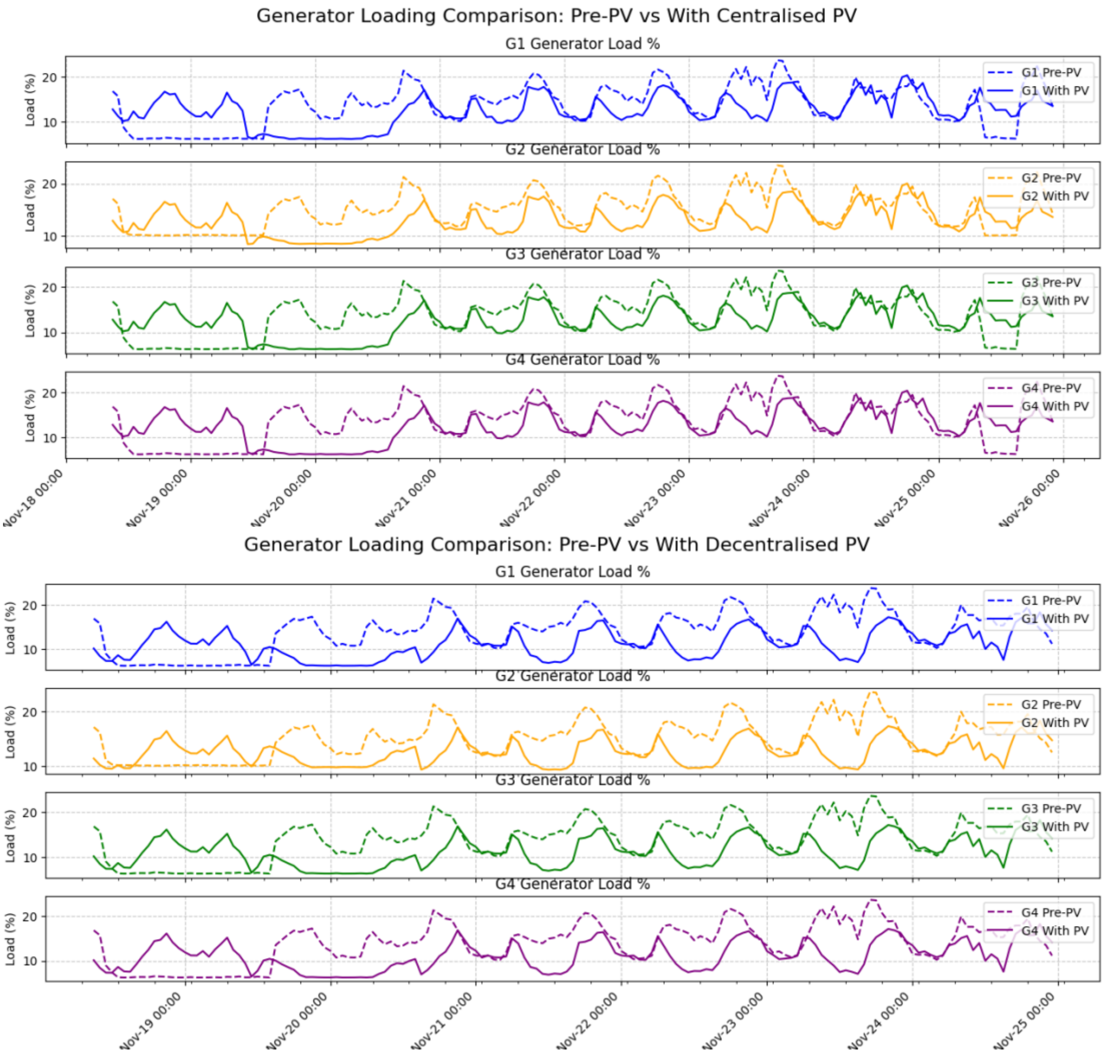

Figure 10. The effect of 250kW centralised (top) and 250kW decentralised (bottom) PV systems on generator loading (%)

4.2.7. Grid motoring

A potential peculiar effect of adding the VRESs to the grid is motoring. In this phenomenon, generators absorb power from the grid, rather than pushing power to it. In other words, the generators act as motors. This can cause damage to the turbines, and cause stability issues. Motoring occurs in this case, because at certain points in time, the PV system produces more power than there is load on the grid to absorb it.

In this depiction of the Rakiura Stewart Island grid, both centralised and decentralised PV systems induce motoring in the generators (see Figure 11). The effect is intensified as the size of the PV systems increase. In general, the decentralised systems caused marginally more instances of motoring, and more intensive energy absorption. These motoring events happened mostly when there was no load, but the PV system was still producing power, though there were some instances where though there was load motoring still occurred.

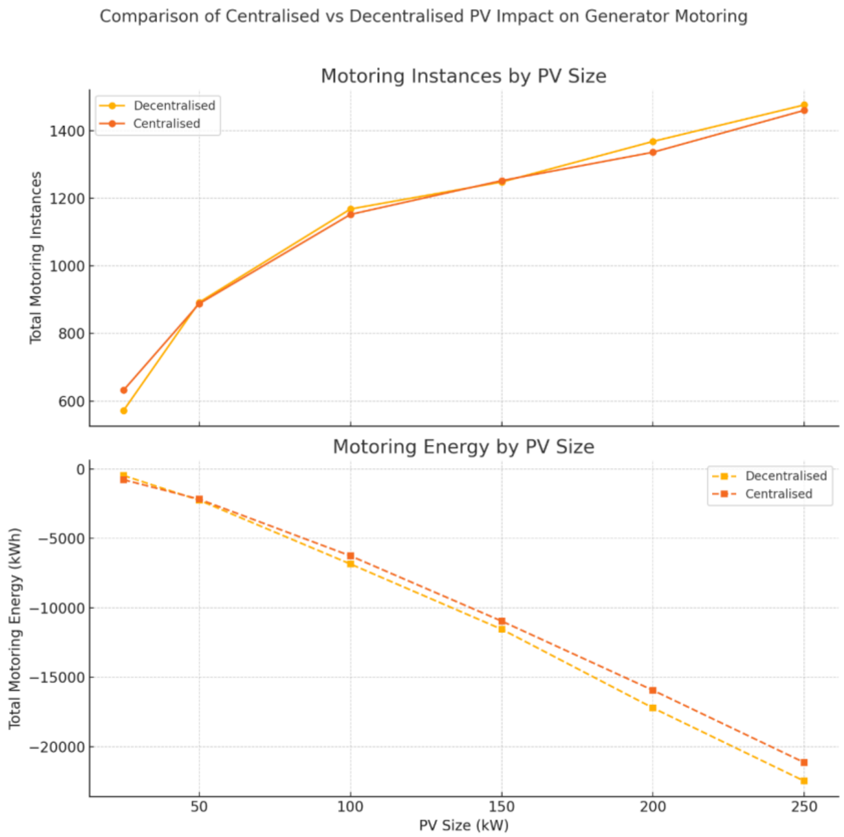

Figure 11. PV system impact on generator motoring

Motoring can be a catastrophic issue to generators but could be avoided by having protections in place. These include having reverse power relays that would trip the generator's circuit breaker if reverse power flow is detected. At the renewable energy source, output can be curtailed if it is producing excess power. Here, the PV inverters will reduce their output if they receive a signal that the combined output of the PV system and the generators is higher than load demand. Finally, excess power from PV systems can be stored in battery energy storage systems.

4.3. Discussion

Voltage increase was seen with both centralised and decentralised PV systems. The level of increase is dependent on the season, and the solar output. Decentralised PV systems resulted in more marked voltage rise, in particular at nodes that were further from the power plant. This could be explained by there being reduced impedance between the point of generation and load consumption points. While voltages in this project remained within an acceptable range, the larger variance may necessitate enhanced voltage regulation techniques, such as smart inverter integration or volt-VAR control.

Reduction in voltage drop was best achieved with decentralised PV systems, particularly on long lines. This shows that placing generation closer to the load improves the voltage profile and efficiency. This is very useful point to absorb for grids such as Rakiura Stewart Island with is low inertia, but also long and skinny.

Line loading was decreased with both centralised and decentralised PV systems, but decentralised systems gave rise to more widespread and effective reductions. Transformer loadings though, saw loading increase in decentralised systems as more load is injected directly to the transformer. The takeaway, therefore, is that care must be taken if installing decentralised PV systems that equipment is properly sized. In the case of pre-existing grid conditions, upgrades might need to be carried out.

Line losses decreased with a decentralised PV system where it was mostly static with a centralised system. This is due to decentralised PV generation being closer to the loads, which reduces the current through longer transmission lines.

Generator loading % was decreased with the installation of both centralised and decentralised PV systems compared to the baseline prior to installation. Decentralised PV systems were more effective as they can reduce local demand more effectively, relieving stress on generators. This translates to using less fuel to provide power, which is a boon for places where fuel costs are high due to their location. The generator lifespan can also be increased, which reduces spending if the generators are kept as backup. In addition, the generators can more readily respond to sudden demand spikes and frequency disturbances if they are providing less base load. This improves the overall system resilience.

Results from the simulation has shown that motoring occurs at even low levels of PV penetration on a standalone low-inertia grid, especially during periods where the grid load is low. Both centralised and decentralised systems caused motoring, but the effect is more pronounced in the decentralised setup. This is potentially due to oversupply at the load points without sufficient load to absorb it. While in practise generators have some built in guards against motoring, it does still happen. This highlights the need for micro-grids to have very robust control systems when integrating RES into the grid. Beyond having reverse power relays, smart inverter curtailment and energy storage would be needed to mitigate these issues. Of course, with the introduction of smart into the system, a strong communication network would be necessary, in particular with a decentralised PV system that requires multiple installations in different locations to talk to each other and the power plant to change its behaviour on the fly.

5. Conclusion and recommendations

This research showed how sensitive a microgrid with low-inertia is to the penetration of variable renewable energy sources. In the analysed scenario, Feeder 1 had an annual power output of 663,786kW. Feeder 2 had 1,055,396kW. With even 25kW of VRES penetration, issues such as generator motoring and voltage rise were encountered. These results suggest that the grid would also see frequency rises. As the capacity of VRES penetration increases, the effects are enhanced accordingly. Comparing the results show that negative effects are overall better mitigated by using the decentralised approach, as this offers more even distribution of the generation burden, lower line voltage drops, decreased line losses, and greater line loading reductions. Decentralised systems also have the advantage when it comes to decreasing loading on diesel generators in the grid, reducing fuel use and lengthening the lifespan of the generators. In exchange for these benefits however, decentralised installations introduce higher node voltages and increase coordination complexity for seamless operation.

5.1. Limitations

Certain parameters had to be assumed, such as line type and generator setup. While the assumptions were reasonable and realistic, having access to all the existing grid setup in Rakiura Stewart Island would increase the reliability of the result. In addition, there is no power-flow validation, and so the results can only be taken as indicative trends.

5.2. Contribution of the research

The findings for this research, though based on Rakiura Stewart Island, can be extrapolated to other SIDS, and even micro-grids that are within larger systems that have low-inertia conditions. The study also suggests that a decentralised approach would be best for low-inertia grids. This information is useful for informing policy and planning in areas experiencing this issue.

5.3. Recommendations for further research

Storage is seen as being of utmost significance in the preparation of the grid for variable RES. There are several energy storage systems (ESS), each having unique strengths and weaknesses. Given their versatility in both usage and the forms they come in, there should be deeper investigation into the roles they can play, and how best to integrate them.

In addition to storage the following should be undertaken:

- Investigation into the potential of Flexible Alternating Current Transmission System devices (FACTS) including Static Synchronous Compensators (STATCOM), Static VAR Compensator (SVC) and Unified Power Flow Controller (UPFC) in enhancing power quality in grids with high VRES penetration;
- Exploring the benefits of generator control schemes, particularly when coordinated with battery energy storage systems, to increase grid stability; and
- Studying the transient and dynamic effects on the grid caused by rapid changes in VRES output, for example cloud passing over solar PV systems, to better understand and inform mitigation strategies.

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