Efficient Operation of Diesel Generator Sets in Remote Environments

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Mechanical Engineering

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May 9, 2017
Blacksburg, VA

Keywords: mobile hybrid power system, fuel consumption, energy storage, diesel engine, generator

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Abstract

Diesel engine and generator sets (gensets) have been extensively used for standby and remote power generation over the past hundred years. Due to their use for standby power, these diesel gensets are designed to operate in conjunction with the grid, which relates to a fixed speed operation with a 60 Hz AC output. For operation in remote conditions, such as military and disaster relief applications, this fixed speed operation results in limiting the power output available from the engine, as well as the overall efficiency of the system.

The removal of this grid connectivity requirement could result in an increase in system efficiency. At a given load, the engine operates more efficiently at lower speeds, which corresponds to an increase in the system efficiency. This low speed operation also results in lower power output. Knowledge of the load is important in order to determine the most efficient operating point for fixed speed operations.

Operating at a higher power output for a given speed also results in higher system efficiency. The addition of a battery pack will allow for a higher apparent load, resulting in higher operating efficiency. The addition of a battery pack will also allow for energy storage, which allows for a higher operating efficiency, as well as "engine off time". A controlled series capacitor converter should be used to ensure that the maximum power is transferred from the genset to the battery/load. Knowledge of the load and equipment available should be used in order to determine the ideal dispatch strategy.

Overall, operation at the grid frequency limits the efficiency of the overall system for remote operations where grid frequency is not required. The simulated genset had an efficiency of 24% for a 3 kW when operated at 1800 RPM, and increase from the 17% efficiency at it normal operating speed of 3600 RPM. This corresponded to a fuel savings of 3 gallons over 24 hours of continuous operation. When a battery is incorporated into the system, the efficiency of the system will increase for a given output load. For example, the simulated genset has an efficiency of 15% for a 1 kW load, which increases to 24% when a battery is added and charged at 2 kW.

Efficient Operation of Diesel Generator Sets in Remote Environments

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General Audience Abstract

Diesel engine and generator sets (gensets) have been extensively used for emergency and remote power generation over the past hundred years. Due to their use for emergency power, these diesel gensets are designed to operate in the same way as the grid. This results in a fixed speed operation in order to achieve 60 Hz. For operation in remote conditions, such as military and disaster relief applications, this fixed speed operation results in limiting the power output available from the engine, as well as the overall efficiency of the system.

Increasing the efficiency of the diesel engine will increase the overall system efficiency, which is the relationship between the energy into the engine as compared to the energy produced. At a given load, or energy output requirement, the engine will operate more efficiently at lower speeds. This low speed operation, however, will result in a lower power output. Therefore, knowledge of the load is important in order to determine the most efficient operating point for a diesel engine, and the genset as a system.

Operating at a higher power output for a given speed also results in higher system efficiency. The addition of a battery pack will allow for a higher apparent load, or the load seen by the engine, resulting in higher operating efficiency for the engine. The addition of a battery pack will also allow for energy storage, which allows for "engine off time", or time which the system can provide power silently. Analysis should be conducted to ensure that the maximum power is transferred from the genset to the battery/load. Knowledge of the load and all equipment available should be used in order to determine the ideal charging and discharging strategy for the battery and system.

Overall, operation at the grid frequency limits the efficiency of the overall system for remote operations where grid frequency is not required. A simulation was conducted to illustrate this concept. The simulated genset would save approximately 3 gallons of fuel over a 24 hour operating time when run at of speed of 1800 RPM, as opposed to its normal operating speed of 3600 RPM. When a battery is incorporated into the system, an additional gallon of fuel can be saved over a 24 hour period.

Acknowledgements

I would first like to thank Dominion Power and the Marine Warfighting Laboratory for providing the funding and support for my research.

I would like to thank my committee for their guidance through both my undergraduate and graduate careers here at Virginia Tech. Dr. Wicks, who has supported me though this research and created a very welcoming lab, Dr. Nelson, who first sparked my interest in engines and the automotive industry, and Dr. Southward, who has supported my interest in controls.

I would like to thank my parents, Matt and Jill, my brother, Joey, and all my extended family for their complete support throughout all aspects of life. Without this love support, I never would have reached the point at which I am today, both academically and as a person. I would like to thank my fiancé, Tommy, for being with me every step of the way and supporting my decisions. He has kept me sane throughout this process.

Finally, I would like to thank the members for the Mechatronics Lab, Virginia Tech, and Fairfax County Public Schools. I am here today due to the support, guidance, and academic foundation each has provided me.

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Chapter 1 Overview

1.1 Introduction

For the last one hundred years, the combined machinery of diesel engines and generator sets (gensets) have been extensively used in several fields. One of the primary uses for these gensets is to provide standby and emergency power, such as to a hospital during a power outage. As such, they are designed to be connected to the grid and run at a fixed speed with the standard 50/60 Hz AC output. This 50/60 Hz output is necessary in order to operate installed equipment which usually operates on the grid. However, one of the other primary uses of diesel gensets is to provide remote power, such as for military operations in the desert, and for such cases, the grid connectivity requirement is not necessary.

In cases where grid connectivity is not a requirement, the 50/60 Hz AC output can be very limiting. The output requires the genset to operate at a fixed speed, generally 1500 or 1800 RPM for four pole generators, or 3000 or 3600 RPM for smaller, two pole generators, which may not be the optimal operating point for the engine. Diesel engines typically operate at their most efficient points at about 2000 – 2500 RPM, though it does vary from engine to engine based on design and size. Efficiency is defined as the ratio of power out of the system vs power in. Therefore, the efficiency of a diesel engine (or diesel genset) is the ratio of the power out of the engine (or genset) to the power added to the system in the form of diesel fuel. This efficiency optimization of diesel engines for the speeds of 2000 – 2500 RPM is due to their primary use in the automotive industry. Unfortunately, this automotive optimization does not correspond to the speed of the generators. The diesel engine will likely not operate at its most efficient point when used in a generator set operating at either 1800 or 3600 RPM. In addition, diesel engines are generally not rated for maximum power at 1500/1800 RPM and will have to be oversized in order to meet load demands at lower speeds.

The efficiency of a genset is represented below as a function of load for a fixed speed. Low load operation leads to lower efficiency. The maximum power out is also limited by the operating speed. At high speeds (3600 RPM), the maximum power will be higher, but the output load percent will be lower, decreasing the efficiency. At low operating speeds (1800 RPM), the maximum power will be lower, increasing the efficiency of the load, but the output power will be limited. The efficiency of the system could be improved by allowing the speed to vary with respect to the given load, or increasing load to correspond to the maximum output for a given speed.

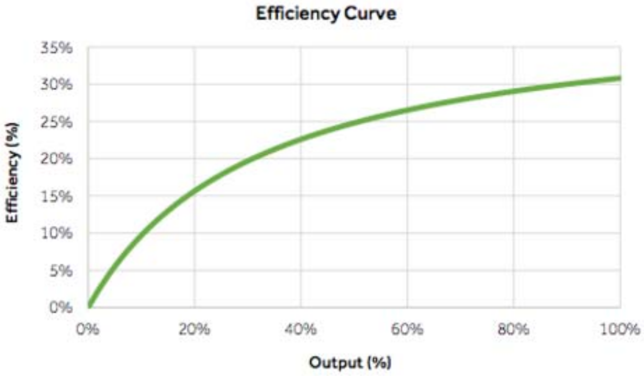


Figure 1. Example of a genset efficiency curve [1].

In this study, various operating conditions of diesel gensets are investigated for the use in remote applications to determine if more efficient operating conditions can be developed when the standard grid requirements are no longer vital.

1.2 The Grid

As mentioned before in Section 1.1, the electric power system (grid) requires that interfacing systems, both which generate and use electricity, operate under very strict constraints. To better understand these constraints, the way power is generated and transmitted needs to be understood. Power generation occurs in large plants, using either combustible fuels (coal or natural gas) or noncombustible (wind, solar, nuclear) fuels [2]. Transmission lines then carry the electricity at high voltages from the power generation centers to the substations or transformers leading to the users. Step down transformers are then used to reduce the voltage to for final consumption. This process can be seen below in Figure 2. Today, the US electrical grid, and some others worldwide, operate at 60 Hz AC electricity, while most of Europe's electrical grid operates at 50 Hz. These standards date back to almost the beginning of electrical generation in the 1880s.

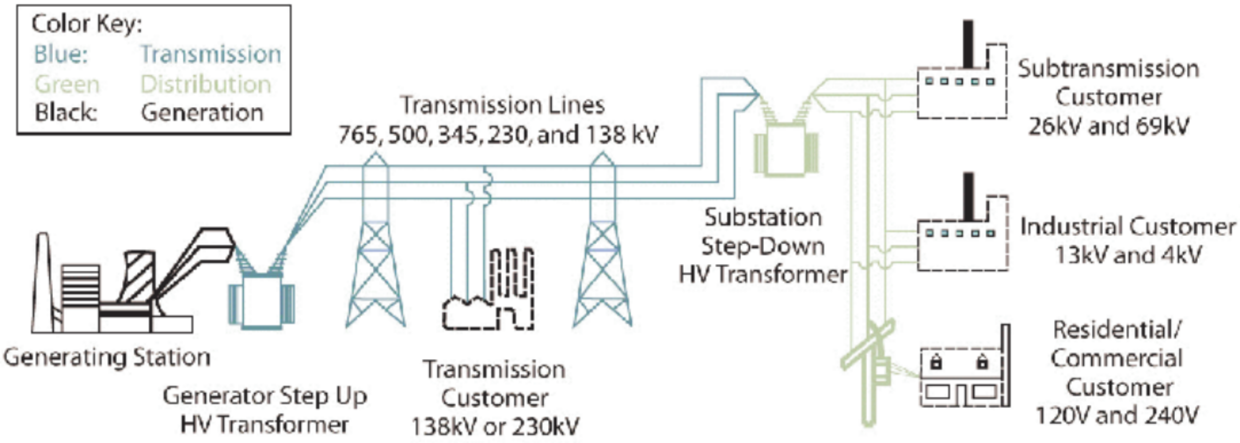


Figure 2. Example of grid layout [2].

While people today take this electrical grid configuration for granted, there was a big debate in the late 1800s about how to set up the power grid. In 1799, Alessandro Volta created the first electric battery [3]. This battery, like those today, operated using a constant, DC current. Using such a battery, Humphrey Davey found that it was possible to produce a continuous, illuminating electric arc in 1809 [3]. When efficient electric generators became available around 1870s, this "arc lighting" was widely used to light buildings and public spaces, such as streets and railroad terminals [3]. In 1879, Thomas Edison lit his Menlo Park laboratory with his incandescent bulbs using a steam powered dynamo [4]. These incandescent lightbulbs were much more suitable for indoor use, and were accepted on a broader scale.

Power systems of this time were almost all DC. AC power was not used as frequently due to concerns of the high voltages that enable long distance transmission. With these concerns of high voltage AC, proponents of DC based power, including Thomas Edison with his DC incandescent bulbs, advocated for uses of DC for city applications. Unfortunately, DC based power came with a major drawback: the transmissibility of DC over a long range. The amount of current able to be transmitted at a specific voltage is directly proportional to the size of the conductor (wire) [4]. It was said that to light Fifth Avenue, a wire the size of a man's leg would be needed. Along with transmissibility issues, DC transformers were very inefficient at the time, so to step down a voltage, a high voltage and low voltage motor would need to be coupled [4].

Due to the drawbacks in the transmission and conversion of DC, AC systems became a larger area of research when generators using alternating current were developed as early as 1878. The biggest advancement in AC power systems came in 1882 when Lucien Gaulard presented a transformer that enabled high voltage output of an AC generator to be delivered to lower voltage local circuits [4]. The first demonstration of long distance power transmission using an AC system came in 1891 by a German firm at the International Electrical Exhibition [3]. Shortly after in 1895, GE and Westinghouse collaborated on the Niagara River Project, transmitting AC power over 20 miles to the city of Buffalo, NY [3].

During this time of power transmission advancement, there was no clear standards for power transmission. The designer of each system had control over the frequency and phases of the electricity transmitted. Frequencies used ranged from 25 Hz (in the Niagara River Project) to 133 Hz (with Tesla's AC generator) [4]. In 1896, Westinghouse and GE announced a cross licensing agreement. With both companies providing additional research, the standard of 60 Hz electricity for lighting and 25 Hz for heavier power was set by 1900 [4]. As such, subsequent AC distribution systems and equipment that came out after this time operated at these specified frequencies, which has continued to be the standard.

The grid today is similar to that of the early twentieth century, with electricity being primarily generated using water based power for hydroelectric dams, as well as coal, natural gas, and nuclear power plants. As of late, renewables in the areas of wind and solar are also being used in practical applications. The use of renewable energy sources and energy storage systems (such as batteries) has caused a rise in the number of “micro-grids”, or grids that can disconnect from the grid as a whole [5]. Additionally, many of the devices people use in their everyday lives, such as computers, small electronics, and LED lightbulbs, operate on DC power [6]. The use of AC power, specifically 60 Hz AC power, is becoming less of a necessity.

1.3 Diesel Engines

Since the beginning of recorded history, humans have harnessing the energy in nature for their own use. Beginning with fire for light and heat, then with domesticated animals such as horses and oxen for agricultural work and transportation, the necessary energy was harnessed and implemented for immediate use. In 1769, James Watt introduced the first practical steam engine, with many improvements being made over the upcoming years, and the first installed in 1776 [4]. After this point, the steam engine was rapidly utilized, from power plants, to transportation. The main reason for this rapid implementation is that the steam engine could provide more usable power than the horses and oxen used before.

In 1892, Dr. Rudoph Diesel patented the first diesel engine, which can be seen in Figure 3. This new engine harnessed power from coal and other fuels, as opposed to solely from the coal used in a steam engine. The original patent was for an engine that burned powdered coal that was blown into the engine cylinder by compressed air, though the specific fuel type was not indicated [7]. Modern engines use liquid fuel. Early diesel engines weighed 250 pounds per horsepower [7]. Even with this high weight to power ratio, diesel engines were significantly more efficient than other engines of the time. A locomotive steam engine had an efficiency of approximately 8%, while a diesel locomotive has an efficiency of 32% [7]. For example, a diesel train had the ability to travel cross country for approximately $83, while a standard steam train would make the same trip using about $300 in coal [7].

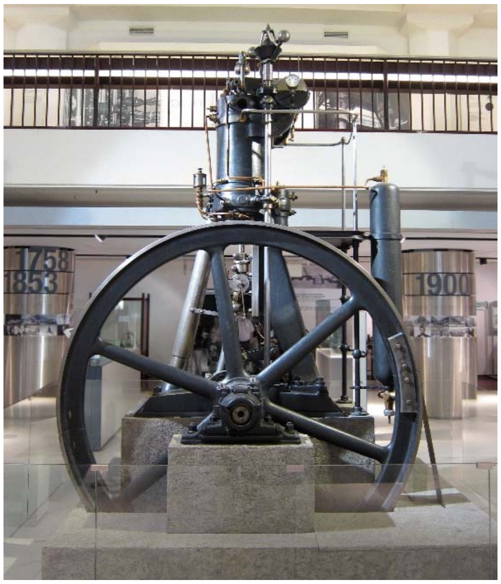


Figure 3. First diesel engine patented by Rudolph Diesel in 1892 [8].

In the 1880s, with the introduction of the incandescent lightbulb, this energy harvesting became more wide scale, with large power stations using steam turbines connected to generators. The reason steam turbines were more wide spread was because at the time diesel engines were too heavy and too expensive to implement for large scale electricity even though they were more efficient. Thankfully, diesel engines could replace smaller scale generators for such applications as those performed by Thomas Edison in his early experiments rather than the steam dynamo. Diesel engines were widely used in both small scale transportation, such as automobiles, and large scale transportation, such as trains and ships, in addition to manufacturing industries.

By the 1950s, the military was using diesel gensets to provide power on the war front. After the implementation for war time applications, diesel gensets have been used in remote environments. In addition, some variable speed gensets have been introduced for remote applications which allows the engine to operate at a variable speed, where the electricity from the generator is rectified then inverted it to a fixed frequency. This method can also be used for gensets which are connected to the grid. This study focuses on the efficiency of diesel gensets in such environments under normal operating conditions, as well as determine if unconventional operating conditions, such as variable speed operation, could result in a more efficient operation.

Chapter 2 Literature Review

2.0 Chapter Overview

This chapter details the literature review conducted for this thesis. The topics covered are variable speed gensets, battery discharge strategies, and maximum power transfer.

2.1 Variable Speed Gensets

In the industry of power generation, diesel gensets have been used extensively over the past 100 years. This is especially true when related to the implementation of power generation in remote areas. Remote power generation is a constantly growing sector, with interests in defense applications, telecommunications applications, and humanitarian efforts such as refugee camps. As remote generation increases, research into diesel gensets, particularly small and portable modules, intensifies. This recent surge in the research of diesel gensets maily focuses on increasing efficiency, and thereby, decreasing fuel consumption. Both of these qualities would allow diesel gensets to be more economically feasible, as well as more environmentally friendly with lower fuel use.

As stated in Section 1.2, diesel gensets consist of a diesel engine and a synchronous generator. Generators were originally designed for large scale applications, interfacing directly with the grid, operating at either 50 or 60 Hz. To produce these frequencies, the engine must operate at either 1500 or 1800 rpm for a four pole generator. The number of generator poles has an inverse relationship to the generator speed as seen in Equation 1:

$$f = \frac{NP}{120} \tag{1}$$

where f is the desired output frequency, N is the operating speed of the generator, and P is the number of poles in the generator. For example, a 2 pole generator would require an engine speed of 3600 rpm to produce a 60 Hz output. Four pole generators are the most widely used in remote power generation, though two pole generators are commonly used for low (<10 kW) power output.

When it comes to increasing overall diesel genset efficiency, the synchronous speed operation of the engine is the limiting factor. Engines are not always optimized to run at these low, synchronous speeds of 1500 or 1800 RPM. Due to the grid connectivity requirement, diesel gensets can include an engine that is t 50% larger than necessary in order to provide sufficient power at low (1500/1800

RPM) speeds, as seen in Figure 4, or are run at inefficient points at high speeds (3000/3600 RPM), as seen in Figure 5 [9]. Another key feature of the engine curve is the torque – fuel consumption correlation. As the required torque decreases, the fuel consumption increases. Therefore, for the same power output, an engine will operate more efficiently at lower speeds. These statements illustrate that by constraining the operating speed of the engine, efficiency of the engine is limited.

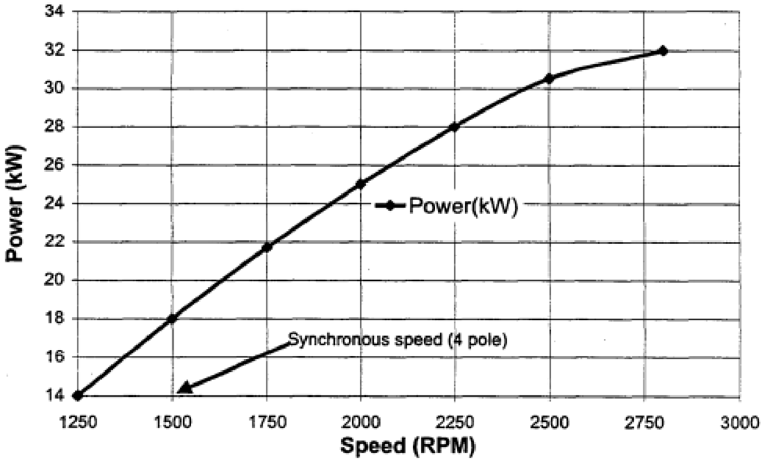


Figure 4. Example of a diesel engine power-speed curve. A genset with four pole generator operating at 50 or 60 Hz with result in an operating speed 1500 or 1800 RPM, limiting the available power out of the engine. [10].

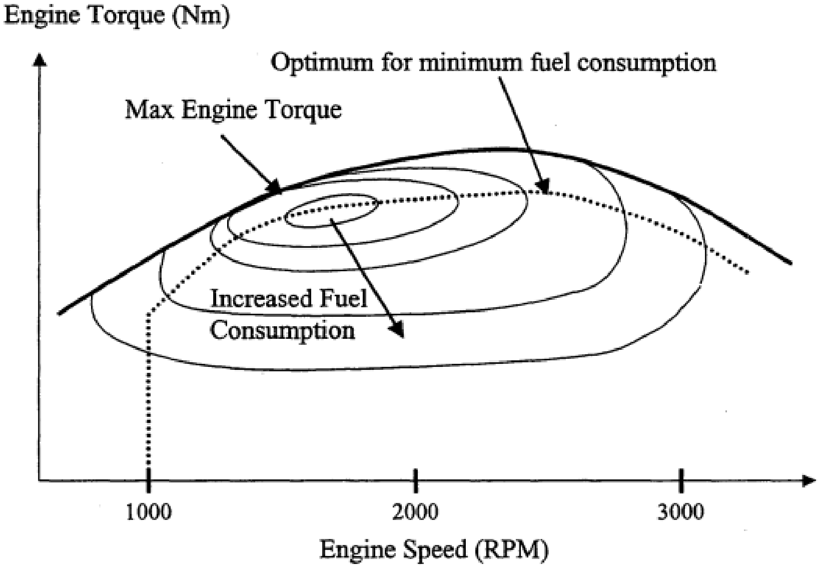


Figure 5. Example of a diesel engine torque-speed curve. A genset with two pole generator operating at 50 or 60 Hz with result in an operating speed 3000 or 3600 RPM, increasing the fuel consumption for a given load [10] Use of this engine with a 4 pole generator, or operating at 1800 RPM, would allow for operation at its most efficient point.

In general, continuous operation with loads of less than 50% of its maximum rated power is unadvisable, especially at low speeds. Operating in this “forbidden area”, or low power at low speeds, cannot be sustained due to incomplete combustion, which can lead to a decreased engine lifespan [11]. For this reason, dump loads are often added to synchronous generators [11]. These dump loads will increase the apparent load by upwards of 40%, in order to prevent operation in the “forbidden area”, reducing the overall efficiency of synchronous speed diesel generators even further [11]. Along with the decreased efficiency, engines operating continuously at these low speeds can have shorter lifespans due to the increased wear associated with this speed, such as inadequate combustion of the fuel in the cylinder during operation [12].

As mentioned previously, these diesel gensets are designed to interface with the grid, and must output (from the generator) 50 or 60 Hz where a synchronous generator is typically used. Unfortunately synchronous generators are susceptible to harmonics, or the distortion of the normal electrical waveform, when connected to nonlinear loads [13]. While some level of harmonics can be accommodated by most systems, problems can occur when harmonics become a significant component of the overall load. Such problems include overheating, high voltages of circulating currents, considerable energy losses, and even equipment failures [13]. Because of these shortcomings, variable speed operation of the generator input (the diesel engine) is not recommended. These gensets are typically operated with the same input and output frequencies (50/60 Hz), and, for this reason, changing the operating parameters of diesel gensets has not been significant area of research until the past two decades.

However, an increased emphasis on renewable energy and remote power has brought a greater focus on ways to increase the efficiency of these devices. For instance, when harnessing wind power, a constant input speed cannot be guaranteed, and new generator technology was developed to efficiently convert a variable input speed to a constant output frequency. This improved technology can be utilized to develop variable speed diesel gensets. These systems would operate a diesel engine at its most efficient point for a given power output by increasing (or decreasing) the speed, as well as the fuel rate. Variable speed input, constant frequency output generators have existed for a significant amount of time, but have been mainly used in conjunction with wind turbines, which results in a lack of widespread application with respect to diesel generators.

There have been many proposed configurations for variable speed diesel generators, but the primary design is composed of a diesel engine, a generator (typically a permanent magnet generator (PMG) or a doubly fed induction generator (DFIG)), a rectifier, and an inverter [14], [15]. Below are two block diagrams of variable speed generators. Figure 6 illustrates a simplified variable speed generator, and Figure 7 illustrates a Department of Defense specific generator designed by the University of Tennessee. A diesel genset developed for remote application would likely resemble that of Figure 7. Batteries are incorporated for energy storage, before the output is inverted to a selectable AC output. This final inversion is not necessary for all applications.

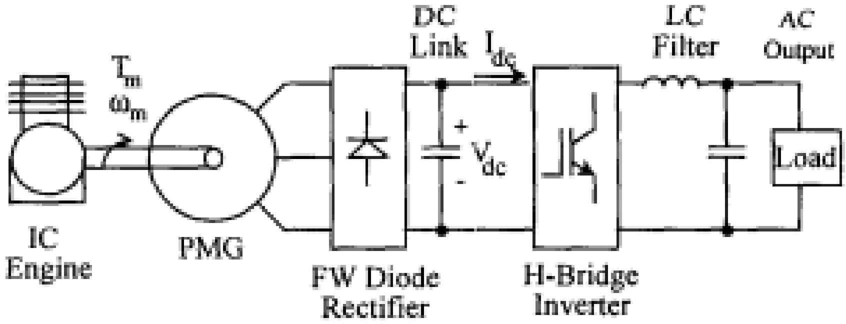


Figure 6. Block diagram for simple permanent magnet variable speed diesel generator [8].

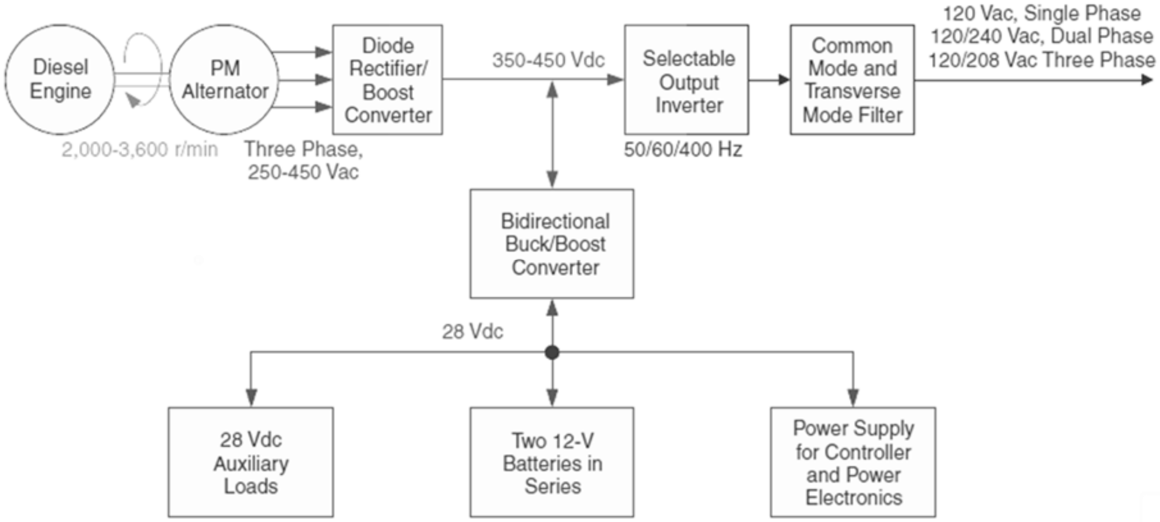


Figure 7. Block diagram for variable speed diesel genset developed for the US Army [9].

While the options for commercially available variable speed diesel gensets are limited, the research field for these devices is still growing. An early study of variable speed gensets was conducted at the University of Massachusetts, Amherst in 1996. The team studied a 15 kW and 5 kW generator at constant speeds and variable speed. The study found that variable speed engines are more fuel efficient than synchronous speed engines for all weather conditions, as shown below in Figure 8 [12]. The variable speed engine had a fuel efficiency of about 11% at low loads, compared to 6% for the constant speed engine. At high loads, the variable speed engine had an efficiency of 21%, compared to 19% for the constant speed operation. Since diesel engines are more efficient at higher loads, it is expected that there is a smaller efficiency difference for these loads.

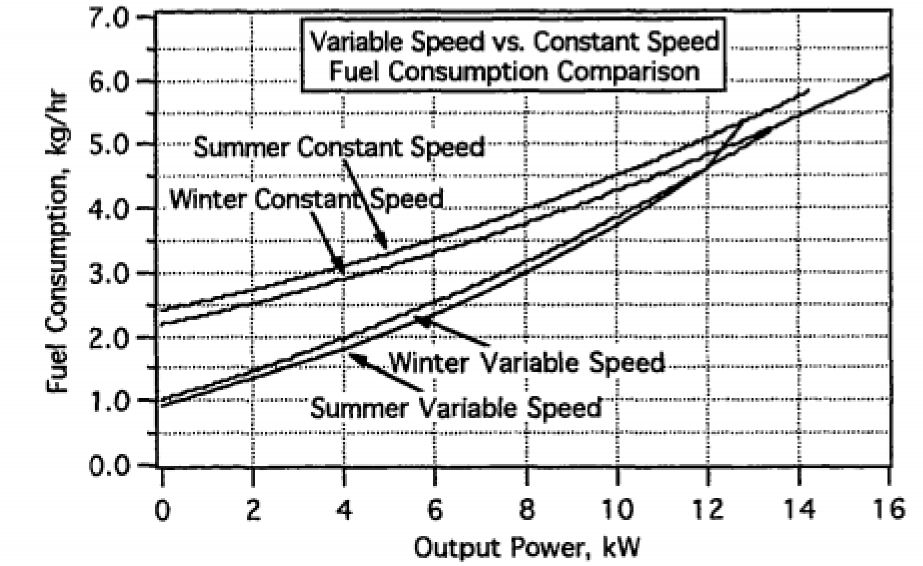


Figure 8. Operation of variable speed and constant speed genset operation under various environmental conditions [12]

The main limitation to variable speed engines is the power conversion necessary to deliver a constant frequency from the generator. This technology has only become wide spread with the increase in renewable power generation, such as wind energy. Both the PMG and DFIG generators have similar efficiencies – approximately 90% with respect to wind power generation (a similar application to variable speed diesel generators) [16]. The necessary power electronics, the rectifier and inverter when in series, have become more efficient, variable speed generators more fuel efficient. For example, in 1994, researchers in Germany measured inverter efficiencies of approximately 90% at full load, with respect to residential solar applications, while in 2010, a study in France found the efficiency of such devices found efficiencies of about 95% [17], [18]. Similar increases can be seen in boost rectifiers, particularly as new switching methods and construction materials are developed, with an increase in efficiency from 90% to over 95%, and upwards of 98% in some cases [19]–[21].

Another major limitation to variable speed gensets is the control systems necessary for their use. The control systems necessary for variable speed operation are drastically different than those for synchronous operation since to the control system must determine the most efficient operating point for a given load, as well as control the speed of the engine. The main difference between the two systems is the ability to provide power during sudden load changes. A synchronous engine can simply change the throttle position to increase or decrease the fuel usage. While there will be some lag in the response, it can generally be done more smoothly than variable speed operation wherethe engine will accelerate (or decelerate) to meet the new load at the most efficient operating point. During this acceleration/deceleration, there will be a period where the load cannot be met and the surge can result in damage to the load [22]. Researchers have found that the addition of a battery pack, or some other storage device, can curb this problem, providing additional power when necessary, but the charging and discharging of this storage device provides another level of complexity to the control system and additional losses.

In addition to the issues concerning diesel engine-AC generator sets described above, there are a few other variable speed genset designs that have been researched over the past decade. The main designs are those that use a continuously variable transmission (CVT) and those which use a DC generator. The CVT gensets use the same variable speed diesel engine and generator as described above, but a CVT couples the engine to the generator to ensure the generator operates at a constant speed [23]. These devices provide less fuel savings than the power electronic gensets (10 – 30% fuel savings, as compared to 20 – 50% for a typical variable speed genset), but tend to be more robust and reliable than the power electronics gensets, and can implement a much simpler control strategy [23]. A genset using a DC generator is very similar to an AC genset, but requires fewer power electronics, providing for a more reliable system [24]. The fuel savings for the AC and DC variable speed gensets are very similar.

Over the past section, implications were made that a diesel generator cannot operate at its most efficient point when connected to the grid. By incorporating additional power electronics, and possibly a battery pack, the diesel engine could operate at a variable speed at its most efficient operating point for a given load. This would allow the engine to be significantly more efficient, thus improving the overall system efficiency. The simple addition of a battery pack to a constant speed genset could also increase the efficiency of the system by increasing the apparent load to the engine, as well as allow for “engine off” time, where the load is powered by the battery. This would also require significantly less tuning of a control strategy for specific uses as is necessary with a full variable speed genset, while also being a more robust, easily maintainable system.

2.2 Battery Discharge Strategies

As identified in Section 2.1, the operation of a diesel genset at a low load will cause low efficiency and high fuel consumption relative to this load at any speed. One way to raise the load is to incorporate energy storage into the system, what is more commonly referred to as a battery cycling system [25]. A rectifier system would need to be added to the output of the generator, as batteries must be charged by a DC input. This rectification creates a DC bus, connected to the input of the generator, or an inverter, and the battery, which could subsequently provide power to the load. Such a configuration would be similar to that of a variable speed generator seen in Figure 7, where a battery is added for sudden load changes. There are two main parameters to consider when developing a battery cycling system: the charging rate of the battery and the depth of discharge.

Battery manufacturers normally provide charging and discharging profiles for their batteries. Such a profile can be seen in Figure 9. Batteries are generally recommended to be charged at a constant current at an initial rate of half capacity (C/2) until at approximately 90% of the battery’s full state of charge (SOC) is achieved [26]. For example, if a battery pack has a capacity of 40 Ah, the charge rate would be 20 A, and a full charge could be reached in approximately 2 hours. While a

C/2 rate is generally recommended, and charge rate up to the capacity (C) is safe; excessively fast charging rates can lead to temperature rise and premature aging of the battery [26]. After the 90% SOC is achieved, the charging will transition to a constant voltage charging until the charge level across each cell in the battery is equal [26].

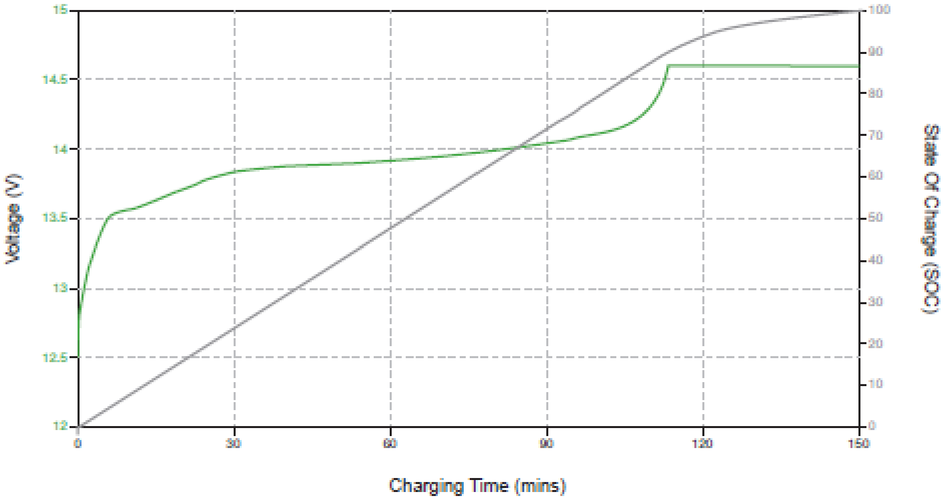


Figure 9. Charging profile for a UCharge battery with a charging rate of C/2. Charging can be is done at constant current up to 90% SOC. After this point, the battery is charged at a constant voltage until the battery reaches 100% SOC [27].

According to researchers from the South China University of Technology, when batteries are used in hybrid systems, there are three main dispatch, or charging, strategy classes [28]. The first, and least complicated, strategy is a load following strategy. With this strategy, the genset produces enough power to supply the load and the battery is charged from renewable resources, such as wind and solar. Battery charging time is dependent on the resources available at a specific time. The second dispatch strategy is a cycle charging strategy. Under this strategy, the genset operates as close to its maximum set point, providing the load with the required power and charging the battery with the excess power. If the maximum power out from the genset would charge the battery at an unsafe rate, the genset will produce the max power necessary for both providing power to the load and charging the battery. The final dispatch strategy class is the micro-cycling strategy. This approach very similar to the load following strategy. The battery is primarily charged using renewable resources. The diesel generator is used to maintain a specific battery state of charge (SOC), with periodic full capacity charging of the battery. With this strategy, the battery is the primary source of power to the load when possible.

The cycle charging strategy is generally considered to be the simplest way to improve generator efficiency [25]. When possible, the battery will be used to power the load, which provides a quiet and fuel-free power source. When the diesel generator is used, it will be operated at a more efficient (higher power) condition. Unfortunately, this discharge strategy does require additional analysis about the equipment used, as well as the depth of discharge (DOD) of the battery. This is a significant area of research, specifically focusing on how the DOD effects the overall cost of the system, the lifetime of the battery, and losses within the battery.

A study was conducted by Delta Energy Systems to show the effects of generator power, and therefore, available charge power, on the cost of electricity generated and the lifetime of the battery [25]. Figure 10 illustrates the full charge of a battery using a 2 kW generator and a 1 kW load. Figure 11 is very similar, illustrating the full charge of a battery, but uses a 5 kW generator with the 1 kW load. Figure 12 illustrates the partial charge of a battery using a 5 kW battery and a 1 kW load. A constant voltage charge was used for initial charging (approximated as constant power charging), with trickle charging at the end of the charging cycle. With an increase in charging power, the operating time for the genset decreases dramatically, and will result in lower fuel consumption. The downside to higher charging is the battery lifetime significantly decreases as well. It is generally recommended to fully charge the battery periodically to extend the lifetime.

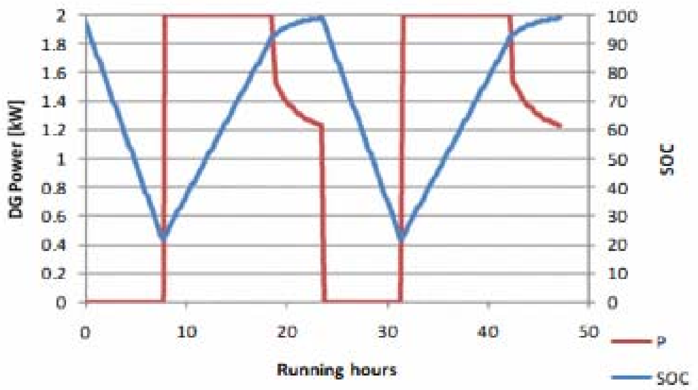


Figure 10. Full charge of sample battery using 2 kW generator with 1 kW load.

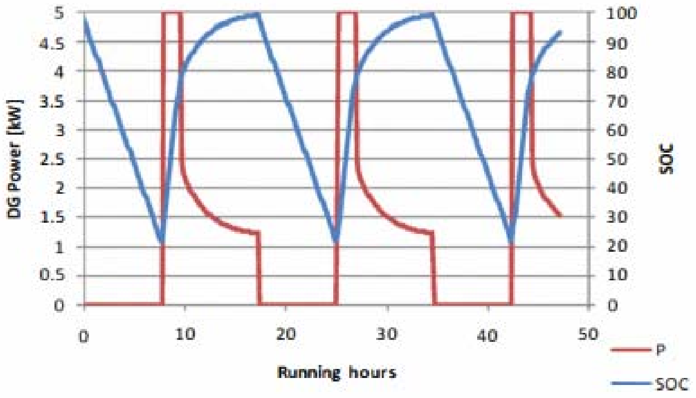


Figure 11. Full charge of sample battery using 5 kW generator with 1 kW load.

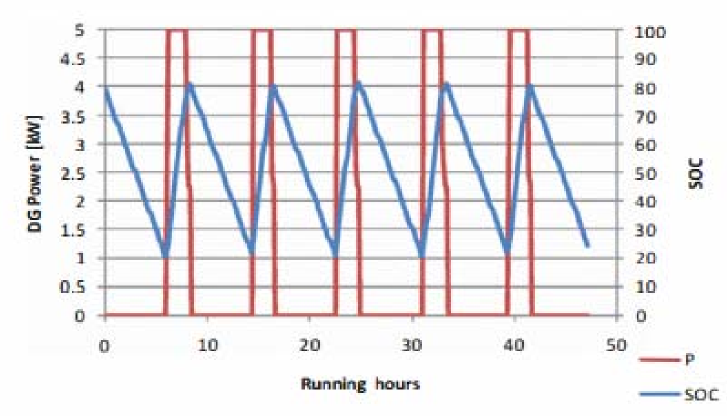


Figure 12. Partial charge (SOC_{max} = 80%) of sample battery using 5 kW generator with 1 kW load.

The researchers from the South China University of Technology also conducted a study to directly show the effects of DOD and charging strategy on the overall cost of the system [28]. Two conditions were studied – full charging of the battery each cycle and partial charging of the battery with periodic discharge. This study found that low DOD discharge resulted in long genset operating hours, and subsequently higher fuel usage, but resulted in longer battery life. In contrast, high DOD resulted in lower genset operating time, lower fuel consumption, and shorter battery life [28].

Overall, to determine the optimal set-points of a given genset-battery system, information must be known about all the physical components in the system, as well as detailed knowledge about the load. If the system is tuned correctly, the addition of a battery to a system can increase the overall efficiency. In order to ensure that the maximum efficiency is achieved, the maximum power must be transferred to the battery and load.

2.3 Maximum Power Transfer

As with most power generation devices, diesel gensets will be connected with a load. The load may be the grid, an electrical device, a battery, or any combination of the three. The main goal when designing a genset is to maximize the power transfer to the load. There are a few ways to analyze this problem, with the main topics of research being the maximum power transfer theorem and power factor correction.

The maximum power transfer theorem states that for a given circuit, the maximum power transferred to the load occurs when the load resistance (DC circuits) or load impedance (AC circuits) is equal to the resistance or impedance of the source. This theory can be explained using a simple two resister circuit as seen in Figure 13 [29].

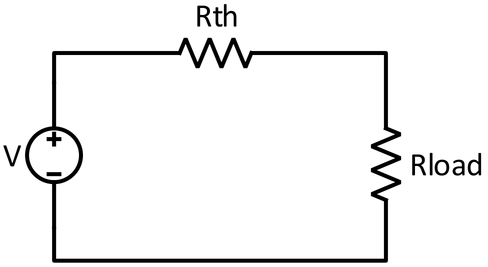


Figure 13. Simple Thévenin circuit.

Ohm's law can be used to determine the current of the system using he known source voltage and resister values:

$$I = \frac{V}{R_t + R_L} \tag{2}$$

where I is the circuit current, V is circuit voltage, R_t is the Thévenin equivalent ristance, and R_L is the load resistance. This current will be the same through the source resistance and the load resistance. The power in the load, P_L, can be represented as:

$$P_L = VI = I^2 R_L = \frac{V^2 R_L}{(R_t + R_L)^2} \tag{3}$$

To determine the maximum power, the derivative is taken with respect to the load resistance and set equal to zero:

$$\frac{dp_L}{dR_L} = \frac{V^2(R_t + R_L)^2 - 2V^2 R_L (R_t + R_L)}{(R_t + R_L)^4} = 0 \tag{4}$$

Solving Equation 4 with respect to the the load resistance, it is found that load resistance (R_L) must equal the source resistance (R_t) to maximize the power transfer. When the load resistance is higher than the load resistance, Equation 2 shows that the overall current will be higher, but results in lower power across the load resistor, as shown in Equation 3. When the load resistance is less than the source resistance, the overall current will be lower, which results in lower power transfer. This is illustrated in a simple circuit simulation in Figure 14.

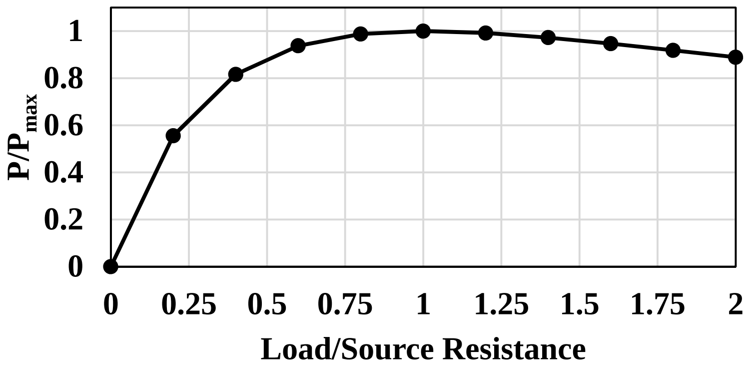


Figure 14. Power to load ratio as a function of load/source ratio. The maximum power to the load occurs when the load resistance is equal to the source resistance.

While the simple analysis is effective for the two resistor circuit as described above, the analysis is not as straight forward for more complex circuits. For most DC circuits, an equivalent circuit can be determined to consist of an independent voltage source and a resistor in series, referred to as a Thévenin equivalent circuit. The Thévenin equivalent circuit can then be used to conduct the above analysis.

As mentioned previously, the maximum power transfer theorem can be used for both DC and AC circuits. The primary difference is that the impedances of the source and load must be equal for an AC circuit, as opposed to the resistances in a DC circuit. Due to this association to both AC and DC circuits, the Thévenin analysis can be applied to develop a single, independent voltage source in series with a single impedance.

This Thévenin analysis can be applied to diesel gensets and their use in remote power generation. An electrical schematic of which can be found in Figure 15a. As illustrated, these devices consist of multiple sources of impedance, including resistors and inductors. In addition, the type of load, such as a battery, must be considered to ensure the maximum power transfer. A schematic of a battery can be found below in Figure 15b, and is also consisting of more than a single impedance. The maximum power transfer theorem can still be used. The below circuit diagrams can be condensed into their Thévenin equivalent circuits, or circuits consisting of an independent voltage source in series with a resistor. Such a circuit would be the same as that of Figure 13, and the theorem can be easily applied. Additional components, such as capacitors, may have to be added in series with the load to ensure equivalent impedance. This analysis can be done with specific equipment and loads in mind to determine the conditions which would result in the maximum power being transferred to the load, though the losses across both the source and load should also be analyzed to ensure there is not an unintended increase in losses

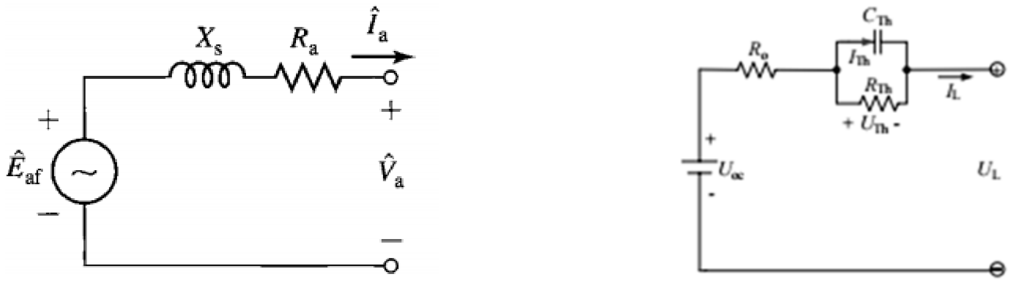


Figure 15. (a) Thévenin equivalent circuit of a permanent generator [30]; **(b)** Thévenin equivalent circuit of a battery. The equivalent resistance must be equal to that of the diesel generator equivalent resistance for maximum power transfer [31].

In addition to the maximum power transfer, the power factor of an AC circuit must be considered. The current, and by extension, the voltage, in an AC circuit take a sinusoidal form, which can be seen in Figure 16, where the voltage can be represented as:

$$v(t) = V_m \cos(\omega t + \theta_v) \tag{5}$$

where V_m is the peak value of the voltage, ω is the angular frequency, and θ_v is the phase angle of the voltage. The current in AC circuits can be represented in a similar way:

$$i(t) = I_m \cos(\omega t + \theta_i) \tag{6}$$

where I_m is the peak value of the current and θ_i is the phase angle of the current. This current, and the phase angle of the current, is directly affected by the impedance in the circuit, or the amount of resistance, capacitance, and inductance in the circuit.

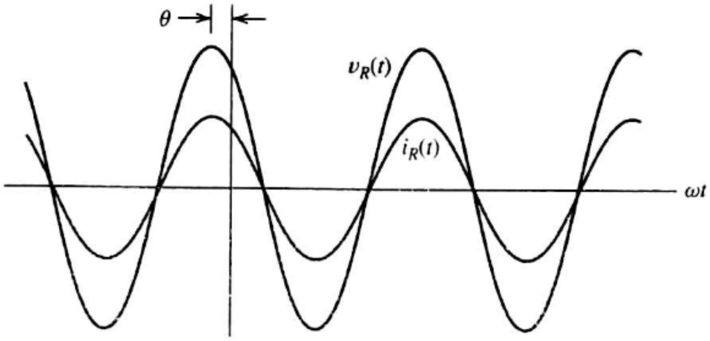


Figure 16. Example of alternating current and voltage vs time [29].

Power in an AC circuit can be represented by:

$$P = V_{rms} I_{rms} \cos(\theta) \tag{7}$$

$$\theta = \theta_v - \theta_i \tag{8}$$

where V_{rms} and I_{rms} are the root mean square values of the voltage and current and θ is the power angle. The power factor can be represented by:

$$PF = \cos(\theta) \tag{9}$$

and is typically represented as a percentage. The power factor represents the amount of power the load receives [29]. The power that is not recognized by the load is called reactive power, and is that power associated with the energy storage elements of the circuit, such as capacitors and inductors. This reactive power can be represented as

$$Q = V_{rms} I_{rms} \sin(\theta) \tag{10}$$

Another way to explain this concept is through the "power triangle", as seen below in Figure 17.

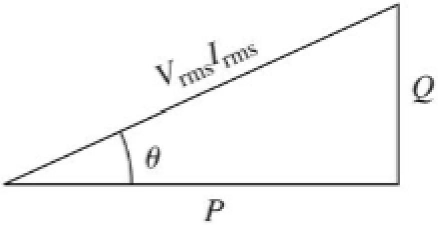
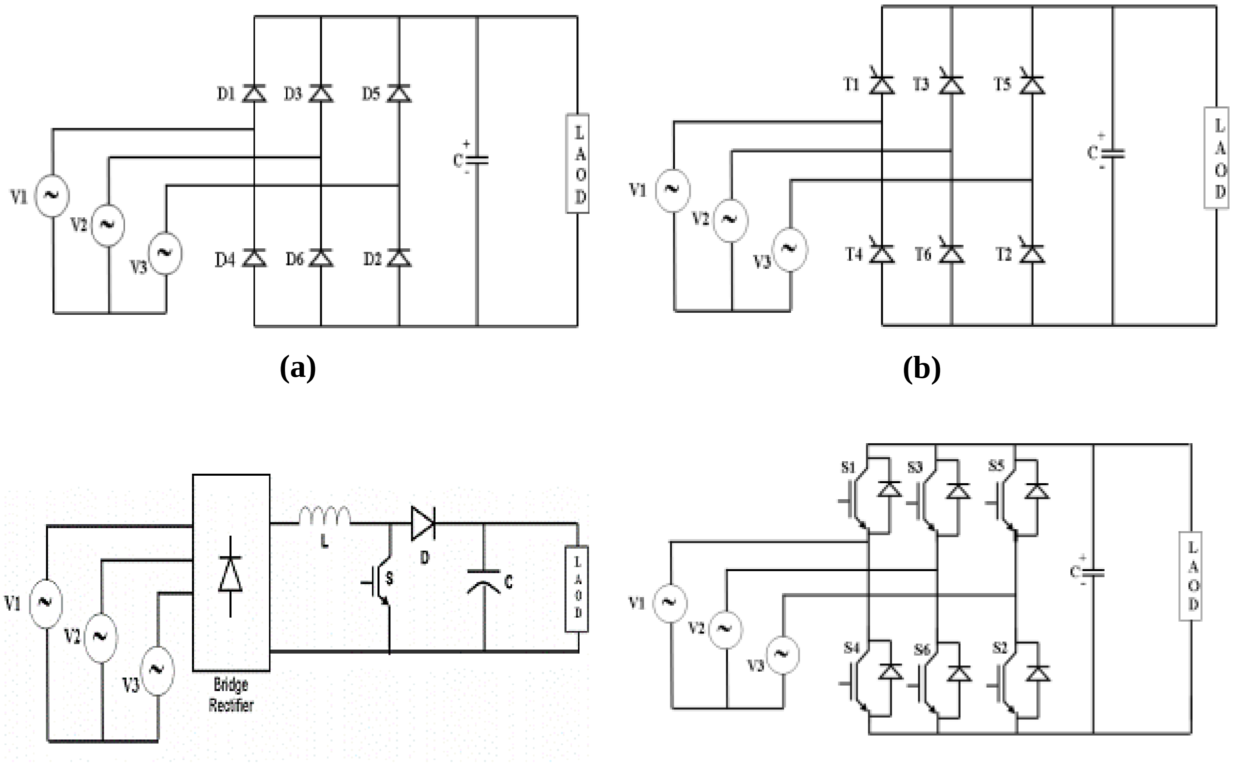


Figure 17. Power triangle for AC circuits relating the real power (P), reactive power (Q), and apparent power ($V_{rms}I_{rms}$) [29].

The power factor is another major concern when considering the maximum power transfer from the genset to the load. If the phase angles of the voltage and current are not the same, less power will be received by the load than is generated by the genset, lowering the overall efficiency and resulting in more fuel consumed. In addition, if the extreme of a power angle of 90° is reached, all the power generated by the genset will be stored as reactive power, with no power going to the load.

Power factor is especially important when considering gensets. The generator used most likely has a unity power factor (power factor of 1). However, a rectifier must be used to convert the electricity from AC (as produced by the genset) to DC (as used to charge the batter pack or supply a DC load). This rectifier can, and likely will, cause the power factor to decrease.

Different types of rectifier circuits exist to convert AC voltage to DC voltage in gensets. The four main types of rectifier circuits are the uncontrolled full-bridge diode rectifier, the controlled full-bridge thyristor rectifier, the uncontrolled full bridge diode rectifier with DC/DC boost converter, and the PWM voltage-source current controlled rectifier [32]. Electrical diagrams for these can be seen in Figure 18. In addition to reducing the power factor of the overall system, adding the rectifier circuit can also result in voltage distortion. When designing a rectifier circuit, little voltage distortion and a high power factor are ideal.



(a) **(b)**

(c) **(d)**

Figure 18. Commonly used rectifier circuits; **(a)** uncontrolled diode bridge rectifier; **(b)** fully controlled thyristor bridge rectifier; **(c)** diode rectifier with boost dc-dc converter; **(d)** PWM voltage-source current controlled rectifier [32].

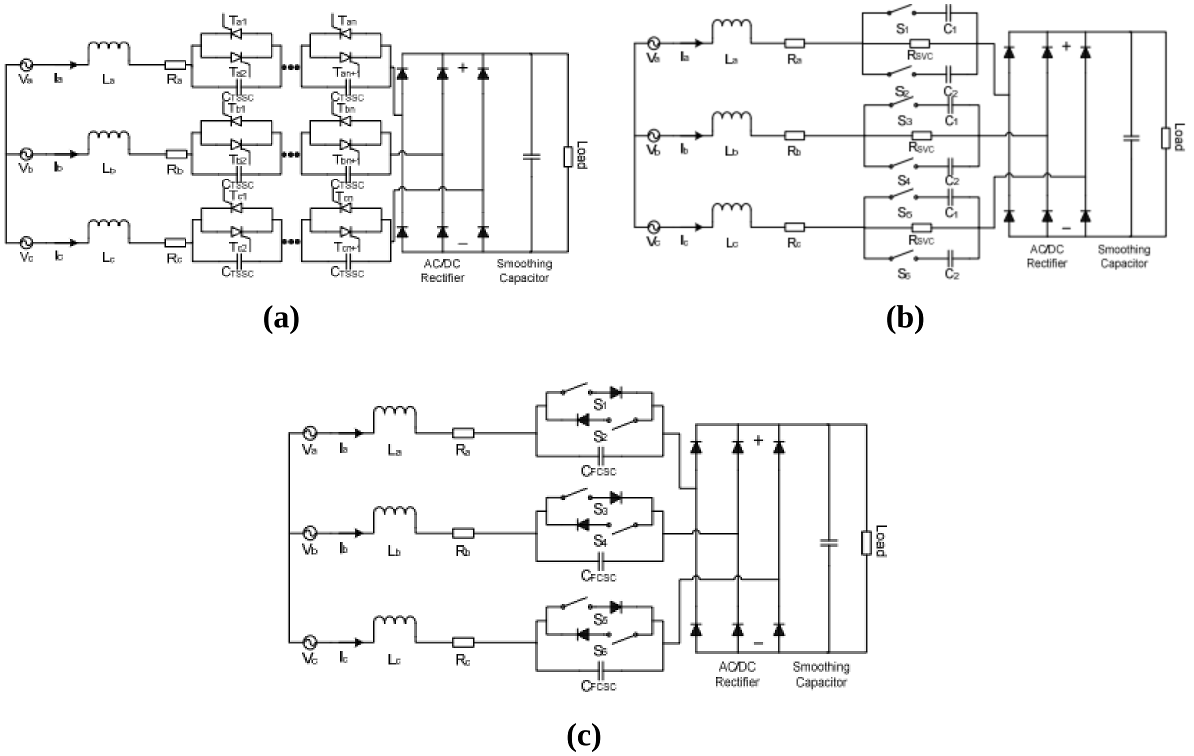
Researchers from Newcastle University simulated the four main rectifier circuits described above for a series hybrid electric vehicle using a PMSG with varying loads. The PMSG operated at 300 Hz, with a peak voltage of 325 V. The results of the simulation can be found in Table 1. A series hybrid electric vehicle is similar to the diesel gensets discussed in previous sections as they consist of a prime mover (the engine) driving a generator, where this output is rectified to provide power to a load, in this case the vehicle and/or the battery pack. Varying loads are especially relevant for both hybrid vehicles and diesel gensets, particularly when charging a battery. A high power factor across all loads is necessary. Each rectifier circuit has similar output voltage characteristics, with a significant voltage distortion at low loads, with an output voltage of approximately 100 V, and little voltage distortion at high loads. The primary difference in these circuits is illustrated in the power factors at different loads. The PWM rectifier has a high power factor at each load. The diode rectifier has a slightly lower power factor, but it is consistent for each load. Both the diode rectifier with boost converter and thyristor rectifier have very large shifts in power factor with varying loads, which is not ideal. A PWM rectifier is the optimal for physical application, though a diode rectifier could also be used. The thyristor rectifier and diode rectifier with boost converter are not suggested due to the significant PF variations with load changes.

Table 1. PF characteristic for four main rectifier circuits [32].

Diode Rectifier	Rload (Ω)	PF	Vout (V)
	1	0.856	106.4
	2	0.840	179.0
	3	0.830	266.2
	4	0.820	316.0
Thyristor Rectifier	Rload (Ω)	PF	Vout (V)
	1	0.480	100.0
	2	0.845	195.0
	3	0.834	263.0
	4	0.823	312.0
Diode Rectifier with Boost Converter	Rload (Ω)	PF	Vout (V)
	1	0.500	98.3
	2	0.850	196.0
	3	0.975	290.9
	4	0.990	380.8
PWM Rectifier	Rload (Ω)	PF	Vout (V)
	1	0.973	85.5
	2	0.973	166.6
	3	0.968	238.3
	4	0.960	304.3

A high power factor and low voltage distortion across all loads are the ideal characteristics for a rectifier circuit. Unfortunately, none of the conventional circuits provided such an output. While the PWM rectifier provided a near unity power factor at each load, and the diode rectifier provided a lower, consistent power factor at each load, both had significant voltage distortion at low loads. Neither would be an ideal rectifier circuit to use in a diesel genset.

While discussing Thévenin equivalence, it was seen that the maximum power transfer for a circuit occurred when the load impedance is equal to the source impedance. One method to ensure this equivalent impedance is to add a capacitor in series with the generator. Some AC/DC converters exist which capitalize on this theory, and are called controlled series capacitor converters (CSC). The Newcastle University researchers also simulated three of these CSC rectifiers: the thyristor-switched series capacitor (TSSC), the switched variable capacitor (SVC), and the forced commutation controlled series capacitor (FCSC), each shown below in Figure 19 [32].



(a) (b) (c)

Figure 19. CSC rectifiers; **(a)** TSSC rectifier; **(b)** SVC rectifier; **(c)** FCSC rectifier [32].

The simulation results can be found in Table 2. As with the conventional rectifier circuits, the PMSG operated at 300 Hz, with a peak voltage of 325 V. As can be seen, all the CSC rectifiers have consistent power factors across all tested loads, with the SVC having the highest power factor of 0.999. This power factor is higher than that of the PWM rectifier, with less fluctuations between loads. The FCSF and TSSC have similar power factors to that of the diode bridge rectifier. Additionally, each of the CSC rectifiers provided a boost in the voltage, with a more consistent output between loads than the conventional rectifiers.

Table 2. PF characteristic for CSC rectifier circuits [32].

	Rload (Ω)	PF	Vout (V)
TSSC	1	0.855	463.5
	2	0.844	485.9
	3	0.832	493.9
	4	0.820	497.9
SVC	Rload (Ω)	PF	Vout (V)
	1	0.999	462.6
	2	0.999	485.3
	3	0.998	493.4
	4	0.996	497.6
FCSC	Rload (Ω)	PF	Vout (V)
	1	0.831	448.0

	2	0.828	476.8
	3	0.832	487.5
	4	0.809	493.0

The DC power from the converter or rectifier system can be used to power a DC load or charge a battery. If an AC output is needed, an inverter can be used to convert the DC electricity to 60 Hz AC. These devices are typically made out of silicone, but inverters made of a silicone carbide – silicone hybrid are also available. The efficiency of both types of inverters is above 90%, with theSiC-Si hybrid inverters reaching a maximum of 97%, and the all Si inverters reaching a slightly lower maximum efficiency of 96%, shown in Figure 20 [33]. The efficiency of these systems can also be evaluated as a function of speed, as shown in Figure 21 [33]. A 90% efficiency can be achieved by across all operating speeds. Diesel gensets have a normal operating speeds above 1600 RPM, resulting in an efficiency of over 95%. These results show that the inversion process can be done with minimal losses.

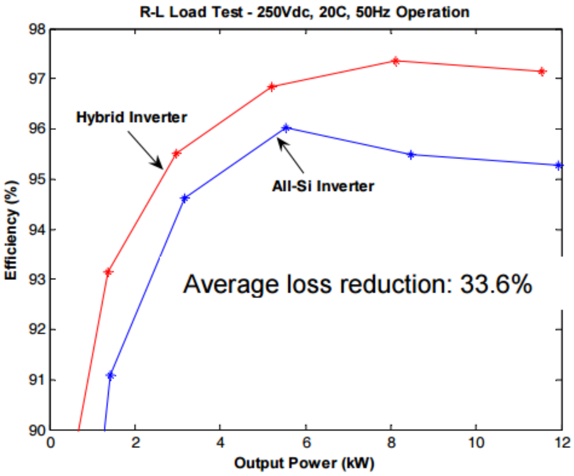
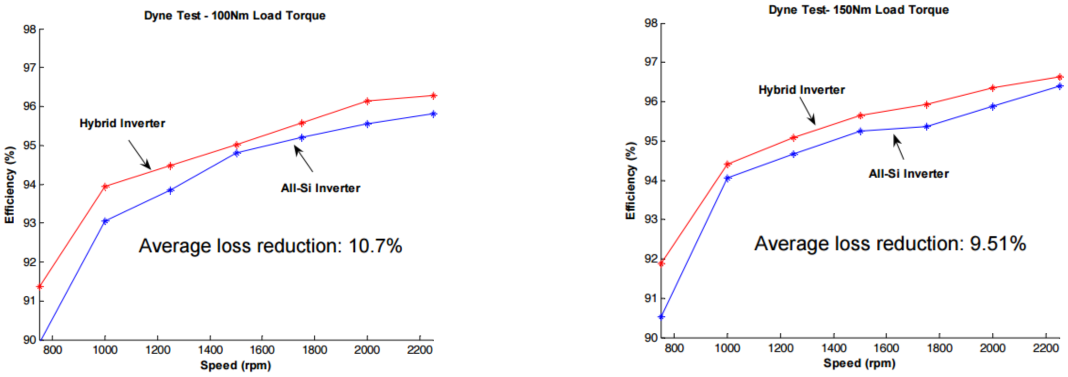
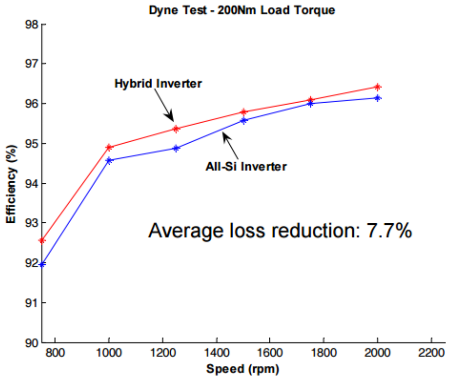


Figure 20. Efficiency of SiC-Si hybrid inverters and all Si inverters. The hybrid inverters have lower losses across all loads [33].



(a) **(b)**



(c)

Figure 21. Inverter losses as a function of speed for different load torques. An efficiency greater than 95% is achievable at speeds greater than 1800 RPM, the normal operating range of diesel gensets. **(a)** 100 Nm load torque; **(b)** 150 Nm load torque; **(c)** 200 Nm load torque [33].

The maximum power transfer is an important aspect to consider when developing a diesel genset. The internal characteristics of the generator must be considered, as well as type of load and rectifier used. As detailed, it is possible to achieve near unity power factor using a SVC converter, though the PWM rectifier can also be used to achieve a high power factor, with voltage distortion. If an AC output is necessary, in inverter can be used. For normal operating speeds of a diesel genset, an inverter can operate with above a 95% efficiency. The rectification – inversion process can be done with minimal losses, so a 60 Hz output from the generator is not necessary.

Chapter 3 Modeling

3.0 Chapter Summary

The following chapter will detail the modeling of the engine and generator, the calculation of the engine and generator efficiencies, and how these can be used to model the genset and determine overall system efficiency.

3.1 Engine Modeling

With respect to a diesel genset, the engine is the prime mover, to which liquid fuel (diesel) is added, and mechanical torque is delivered to the system. In order to begin engine modeling, the basics of engine design and operating parameters were considered. Current diesel gensets operate at a fixed synchronous, AC speed, which may not be the optimal operating condition of the diesel engine. Figure 5 is an example efficiency map for a diesel engine. A more exact curve can be seen in Figure 22, with the addition of power curves. As illustrated, the highest efficiency for this example engine is approximately 35%, and can be achieved by a number of operating conditions, including operating at a torque of 170 Nm at 1800 RPM or 200 Nm at 2200 RPM. This contour plot illustrates that a fixed speed operation is not optimal, especially at lower loads and higher speeds.

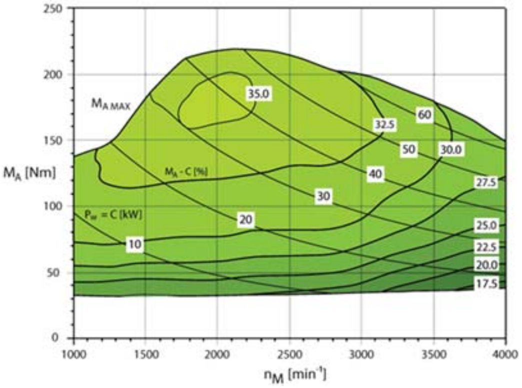


Figure 22. Example of a contour plot for a diesel engine with power curves [34].

In order to create an accurate efficiency map, load testing would be conducted on a physical engine. This process, however, is very expensive and time consuming, and not feasible for this analysis. While this testing is performed by the engine manufacturer, the data is difficult to obtain because manufacturers consider this information proprietary and share only specific information, typically only maximum operating conditions. Alternatively, an engine model was developed in Matlab.

Equations used for engine design, coupled with what information is typically provided by manufacturers, were used to construct a realistic engine simulation.

The primary parameters to consider when modeling an engine is operating pressure, also called the mean effective pressure (MEP), operating torque, and output power. Torque is a measure of an engines ability to do work, while MEP is a calculated parameter used to determine an engine's relative performance [35]. Equations 11 and 12 show the relationship between engine torque, engine power, and MEP.

$$P = 2\pi NT = mep * \frac{V_d N}{n_R} \tag{11}$$

$$mep = \frac{P n_R}{V_d N} = \frac{6.28 n_R T}{V_d} \tag{12}$$

where P is power in W, N is engine speed in rev/s, T is torque in Nm, n_R is the number of crank revolutions for each power stroke per cylinder (two revolutions for a four stroke engine), V_d is the cylinder displaced volume in L, and mep is the mean effective pressure in kPa.

When analyzing engines, the brake mean effective pressure (BMEP) is the focus of analysis', as this is the usable work delivered by the engine to the load. The indicated mean effective pressure (IMEP) is the sum of the work available at the shaft (BMEP) and the work required to overcome the engine losses, represented as friction mean effective pressure (FMEP) [35]. The relationship between BMEP and IMEP can be described as:

$$imep = bmep + fmep \tag{13}$$

where IMEP, BMEP, and FMEP are in terms of kPa.

The maximum BMEP (and/or maximum torque) for each operating speed is generally provided by engine manufactures and can be used as the upper limit. If the maximum MEP or torque is not provided, commonly accepted value for these parameters can be assumed for modeling purposes. For example, naturally aspirated four stroke diesel engines have a maximum BMEP of 700 – 900 kPa, with the BMEP at the maximum rated power of about 700 kPa [35]. These estimations can be used to develop a generalized engine model in terms of output and efficiencies, and can be refined if more information becomes available. A BMEP array, or an array of possible BMEP at a given speed, can then be used to determine the power output for different torque (BMEP) and speed combinations.

The output power can subsequently be used to determine the overall efficiency of the engine. Efficiency of a combustion engine can be defined by Equation 15:

$$\eta_f = \frac{P n_R}{m_a N Q_{HV} \left(\frac{F}{A}\right)} \tag{14}$$

where η_f is the fuel conversion efficiency, which can also be considered the overall efficiency, m_a is the mass of air inducted into the cylinder per cycle, Q_{HV} is the heating value of the fuel used, and $\frac{F}{A}$ is the fuel to air ratio, with other variables defined above. Unfortunately, both m_a and $\frac{F}{A}$ can be very difficult to model. These variables are also dependent on the load and operating speed, which is generally not provided by the manufacturer. This lack of information makes using Equation 14 very difficult for modeling without additional information.

Overall efficiency of an engine can also be predicted by determining the major losses in the engine. For example, the major losses in automotive engines are thermodynamic, or heat, losses and mechanical, or friction, losses. These losses can be incorporated to estimate overall efficiency using Equation 15:

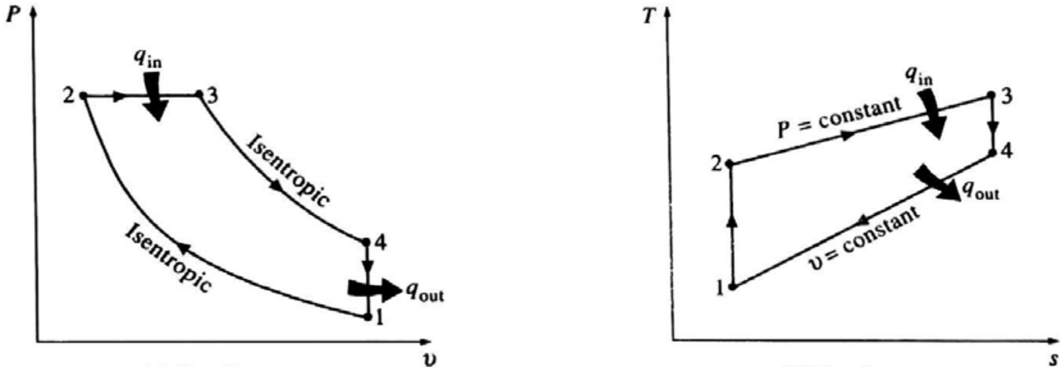
$$\eta_f = \eta_{th} \eta_{mech} \tag{15}$$

where η_{th} is the thermodynamic efficiency and η_{mech} is the mechanical efficiency.

The cold air standard can be used to evaluate η_{th} [36]. In Figure 23, the T-s and P-v diagrams for an ideal Diesel Cycle can be seen. The thermal efficiency can be determined using Equation 16:

$$\eta_{th} = 1 - \left(\frac{1}{r^{\gamma-1}}\right) \frac{\left(r_c^{\gamma} - 1\right)}{\gamma(r_c - 1)} \tag{16}$$

where γ is the specific heat capacity ratio, 1.4 for the cold air standard, r is the compression ratio of the engine, which is the ratio between the volumes at the start and end of the isentropic compression stroke, or the ratio between V_1 and V_2, and r_c is the cutoff ratio, which is the ratio of the cylinder volumes after and before the combustion process, or the ratio between V_3 and V_2 [36].



(a) **(b)**

Figure 23. (a) Diesel Cycle P-v diagram; **(b)** Diesel Cycle T-s diagram [36].

The compression ratio for a diesel engine is typically between 12 and 24, which is commonly reported by the engine manufacturer. For a given engine, the cutoff ratio is difficult to determine without physical testing, but typically has a value between 1 and 4. Isentropic ideal gas relationships can be used to express the cutoff ratio in terms of temperature as opposed to pressure. For a constant pressure process as shown in operating points 2 and 3 in Figure 23, the relationship between the two states can be shown as:

$$\frac{P_2V_2}{T_2}=\frac{P_3V_3}{T_3} \tag{17}$$

$$\frac{T_3}{T_2}=\frac{V_3}{V_2} \tag{18}$$

In addition to the constant pressure process, the isentropic process from 1 to 2 can also provide useful relationships, as shown in Equations 19 - 20:

$$\frac{T_2}{T_1}=\left(\frac{V_1}{V_2}\right)^{\gamma-1} \tag{19}$$

$$T_2=T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1} \tag{20}$$

The compression ratio r, a known value, is the ratio between V_1 and V_2. Therefore:

$$T_2=T_1r^{\gamma-1} \tag{21}$$

Therefore, the cutoff ratio can be represented as:

$$r_c=\frac{V_3}{V_2}=\frac{T_3}{T_2}=\frac{T_3}{T_1}\left(\frac{1}{r^{\gamma-1}}\right) \tag{22}$$

where T_3 can be approximated as the flame temperature of the fuel, approximately 2000K for diesel fuel, and T_1 is the inlet temperature of the air, which can be approximated at room temperature, or 300K [36], [37]. The thermodynamic efficiency, η_{th}, can now be easily estimated with known quantities.

The mechanical efficiency, η_{mech}, can also be quite difficult to estimate. The mechanical losses are associated with the power required to overcome friction of the mechanical components in the engine. This can be represented as:

$$P_{ind} = P_b + P_f \tag{23}$$

$$\eta_{mech} = \frac{P_b}{P_{ind}} = 1 - \frac{P_f}{P_{ind}} \tag{24}$$

Where P_b is the brakepower, P_{ind} is the indicated power, and P_f is the friction power. Using this relationship and that shown in Equation 13:

$$\eta_{mech} = \frac{bmep}{imep} = 1 - \frac{fmep}{imep} = \frac{bmep}{bmep + fmep} \tag{25}$$

Unfortunately, friction power can be very difficult to estimate. One method used to estimate friction is the use of a Willans Line, an example of which is shown in Figure 24. This plot illustrates fuel consumption, in terms of grams/s, versus brake mean effective pressure obtained from engine tests at a fixed speed [35]. The resultant line is then extroplated back to zero fuel consumption. This zero fuel consumption is the FMEP of the engine at that operating speed [35]. A Willans Line must be developed for multiple speeds before a trendline can be developed to estimate FMEP at all operating speeds. There is inherent error in this method due to the many extropolations necessary and the slight curvature in the Willans line, but it does provide a reasonable expectation of FMEP. Unfortunately, the lack of operating information available for most engines makes this method difficult.

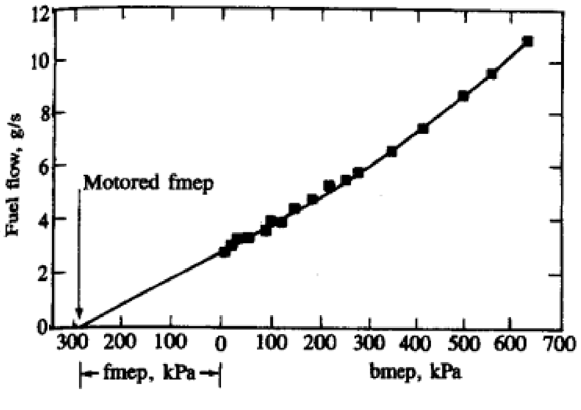


Figure 24. Example Willans Line for a diesel engine, used to determine FMEP for a specific speed.

Another method that can be used is direct motoring tests. This process involves motoring the engine, or operating the engine without firing it, on a dynamometer, measuring the power which has to be supplied by the dynamometer to overcome the frictional losses in the engine [35]. Correlations for a typical engine can be represented as:

$$motoring\ mep = C_1 + 48\left(\frac{N}{1000}\right) + 0.4(2LN)^2 \tag{26}$$

where the motoring mep is an estimate for fmep, C_1 is a correlation constant dependant on the type of engine, and 2LN represents the mean piston speed, with L as the stroke of the engine [35]. The C_1 value is a generalization and can cause increased error in the FMEP calculation. For this reaoson, other motoring FMEP estimators should be used. One of the most common FMEP estimators is:

$$fmep = 6.89476\left(r + 7\left(\frac{N}{1000}\right) + 1.5\left(\frac{2LN}{1000}\right)^2\right) \tag{27}$$

where FMEP is calculated in kPa and r is the compression ratio [38]. This study focused on non-turbocharged diesel engines. This is a better estimation because it is based on engine parameters, not generalizations. These motoring FMEP are accepted as reasonable estimations for modeling if more detailed information is not available [39].

Once a reasonable FMEP model is developed as a function of speed, η_{mech} can be estimated using Equation 25 for any BMEP/speed combination. Subsequently, if η_{th} is known, η_f can be estimated using Equation 15. Once η_f is obtained for each bmep/speed combination, the specific fuel consumption can be calculated using Equation 28:

$$bsfc = \frac{1}{\eta_f\ Q_{HV}} \tag{28}$$

To elaborate, specific fuel consumption is the fuel flow rate per unit output, and is a measure of how efficiently an engine is using the fuel supplied to produce work [35]. The fuel rate of the enfine can be calculated using Equation 29:

$$\dot{m}_f = sfc * P_b \tag{29}$$

This fuel rate is ultimately used to determine how much fuel is used over a specific time period of a given load.

With respect to a diesel genset, the above analysis will determine how much power is transferred to the generator with respect to how much power is provided by the fuel. The next step to determine overall efficiency of the genset is to estimate how much of the power privided by the engine can converted to usable power out of the generator.

3.2 Generator Modeling

The other major component of a diesel genset is the electric generator. The engine provides a torque to the generator, which converts the torque to electric energy. Electric generators and electric motors operate in opposite conditions. A generator receives a torque from a prime mover (the engine) and converts that torque into electric energy. An electric motor receives an electrical input and converts that input to a torque output. Both machines have the same losses and can be modeled in the same way. Additionally, though there are many variations of electric generators and electric motors, they can be modeled in a similar manner. All types of electric generators and motors have four major losses: copper losses, iron loses, friction losses, and constant losses.

Copper losses result from the electrical resistance of the wires and brushes used in the generator. This resistance causes some of the mechanical energy provided by the engine to be turned into heat energy as opposed to electrical energy [40]. Copper losses can be represented as:

$$L_c = k_c T^2 \tag{30}$$

where k_c is a constant depending on the resistance of brushes and T is the torque provided by the engine.

Iron losses are caused by the magnetic effects in the iron of the motor. There are two factors to iron losses: hysteresis and current generation within the iron. Hysteresis loss is the energy required to continually magnetize and demagnetize the iron as the rotor rotates [40]. Losses due to current generation result from the magnetic fields that develop as the iron cores rotate, resulting in additional heat loss. Iron losses can be represented by:

$$L_I = k_i \omega \tag{30}$$

where k_i is a constant and ω is the angular speed of the generator.

Frictional losses develop due to the mechanical nature of the bearings and brushes of the generator. These losses can be represented as:

$$L_f = T_f \omega \tag{31}$$

where T_f is the friction torque.

Windage losses, or the losses due to wind resistance, develop due to the rotating nature of the machine and any fans added for cooling. These losses can be represented as:

$$L_w = k_w \omega^3 \tag{32}$$

where k_w is the windage loss constant depending on the size and shape of the rotor.

The final loss in generators are the constant losses, or those losses that occur even when the generator is stationary. For example, one such loss is the power necessary to operate the controller. This loss is generally denoted as a constant, C.

The above losses can be combined to determine the total losses:

$$total\ losses = k_c T^2 + k_i \omega + T_f \omega + k_w \omega^3 + C \tag{33}$$

Once the total losses have been determined, the efficiency can be determined using the general relationship between input and output powers:

$$\eta_g = \frac{P_{out}}{P_{in}} \tag{34}$$

The output power can be considered the input power from the engine, minus the total losses, or:

$$\eta_g = \frac{P_{in} - (k_c T^2 + (k_i + T_f)\omega + k_w \omega^3 + C)}{P_{in}} \tag{35}$$

An example of overall efficiency can be seen below in Figure 25.

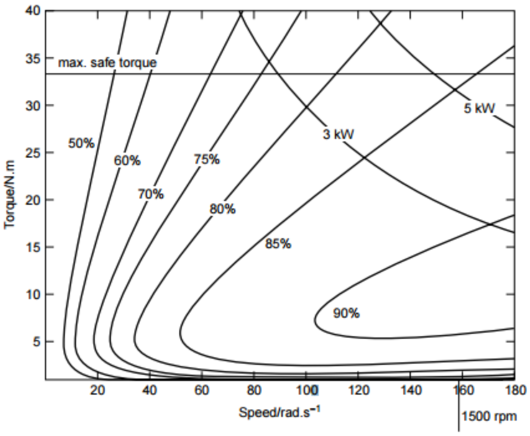


Figure 25. Example of efficiency contour plot for a permanent magnet brushed DC motor that may be used in an electric scooter. The analysis conducted to create this plot is the same as for a generator used in a diesel genset. For example, operation at 1500 RPM with a 10 Nm output with result an efficiency of approximately 90% [40].

Once the efficiency of each of the components has been determined, the overall efficiency can be calculated for any given load/speed combination.

3.3 Overall Genset Efficiency

Ultimately, this analysis is focused on maximizing the efficiency of the genset, not necessarily the maximizing the efficiency of the engine and generator separately. The overall efficiency will be the ratio of the power out of the generator to the power from fuel into the engine:

$$\eta_o = \frac{P_{out,gen}}{Power_{in,eng}} \tag{36}$$

This relationship can also be represented by cascading the efficiencies of the engine and the generator:

$$\eta_o = \left(\frac{P_{out,eng}}{P_{in,eng}}\right)\left(\frac{P_{out,gen}}{P_{out,eng}}\right) = \eta_{eng}\eta_{gen} \tag{37}$$

Using this analysis, the load will be considered the power out of the generator. Given a genset speed, the losses through the generator can be determined. These losses can then be used to estimate the power into the generator, which is also the power out of the engine. The efficiency of the generator can be calculated using Equation 35. Equation 25 can be used in conjunction with an estimate of frictional losses to calculate the engine mechanical efficiency for a given output. The overall engine efficiency can be calculated with an estimation of the thermal efficiency. Equation 36 or 37 can then be used to calculate overall system efficiency. This analysis can be used to optimize system efficiency for a given load.

Chapter 4 Simulation and Validation

4.0 Chapter Summary

The following chapter will detail the simulation and validation of a diesel engine and diesel genset. The operation of the genset at varying speeds will be studied to determine the most efficient operating point. The operation of the genset with a battery is also investigated to determine if such an addition can result in more efficient operation.

4.1 Engine Simulation

The experimental focus for this study will be emphasized for gensets that are capable of being small, portable, and have an output power of 10 kW or less. A market study was conducted, focused on these small gensets, with the goal of validating the models discussed in Chapter 3. Only direct drive gensets were considered. The Kubota GL7000 generator was chosen for simulation. This genset consists of a Kubota Z482 engine and a 2 pole, rotating field electric generator.

As mentioned in Section 3.1, basic engine simulations can be difficult due to the limited information provided by the engine manufacturer. This Kubota genset was chosen due to the amount of information available. The maximum operating conditions as reported by Kubota can be seen in Figure 26, and other engine specifications used for simulation can be found in Table 3. The maximum torque can be used to determine the limits of the BMEP for the engine simulations, so generalized operating parameters do not have to be used, providing for a more accurate simulation.

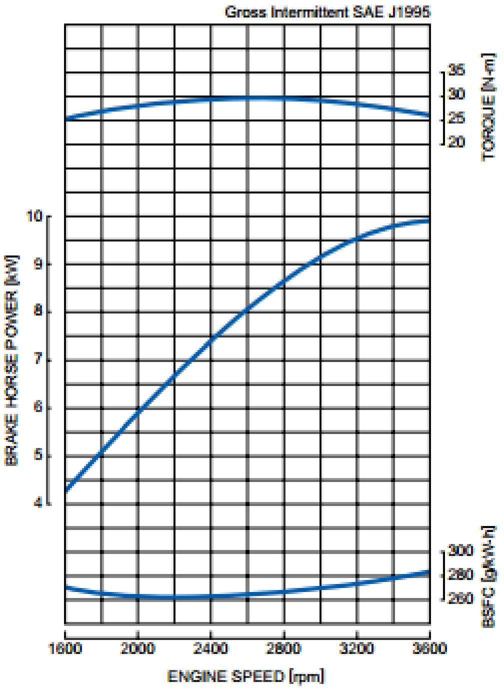


Figure 26. Maximum operating conditions for the Kubota Z482 engine [41].

Table 3. Specifications for the Kubota Z482 engine [41], [42].

Number of Cylinders	2
Bore (mm)	57
Stroke (mm)	68
Displacement (L)	0.479
Gross Output (kW)	9.9
Generator Continuous Output Power (kW)	8.9
Compression Ratio	23.5:1

The primary reason this engine was chosen is that the compression ratio is reported, as this ratio is imperative to determine an accurate thermal efficiency. Using Equations 16 – 22, the thermal efficiency was determined to be 67%, which is very high. Gasoline engines typically have a theoretical thermal efficiency of approximately 40%. Diesel engines will have a higher thermal efficiency due to the higher compression ratio present in these systems (12 – 24 vs 8 – 12). A more realistic thermal efficiency of 50% was used for the subsequent modeling.

To continue with the engine efficiency analysis, the frictional losses (FMEP) of the engine, must also be estimated. The Willans Line is the simplest model to use to estimate friction. However, this model requires knowledge of engine fuel use at different torque outputs at the same engine speed, which is beyond what was provided by Kubota [35]. For that reason, the Millington Model was used [38]. This model, as described in detail above, is an empirical model dependent only on the engine operating speed. A plot of the fmep as a function of engine speed can be seen below in Figure 27. The fmep is roughly linear, though there is a slight curve.

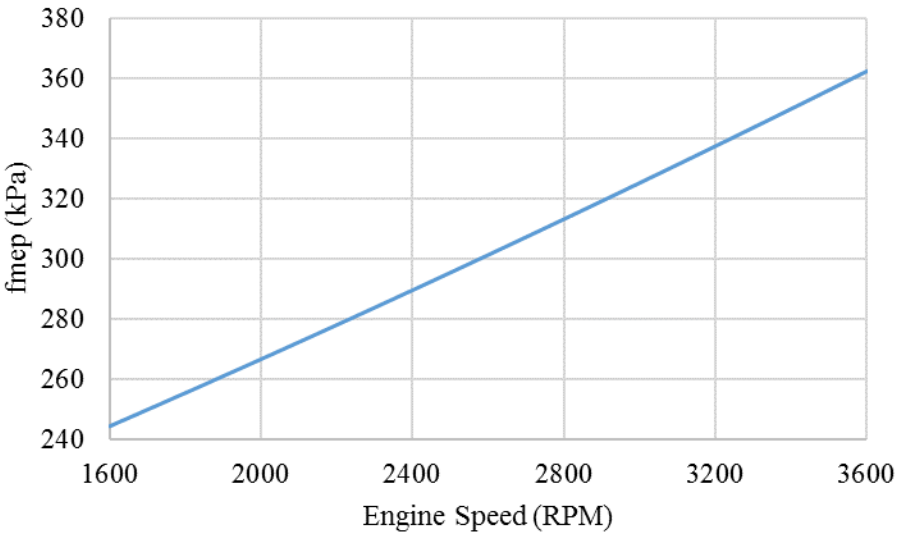
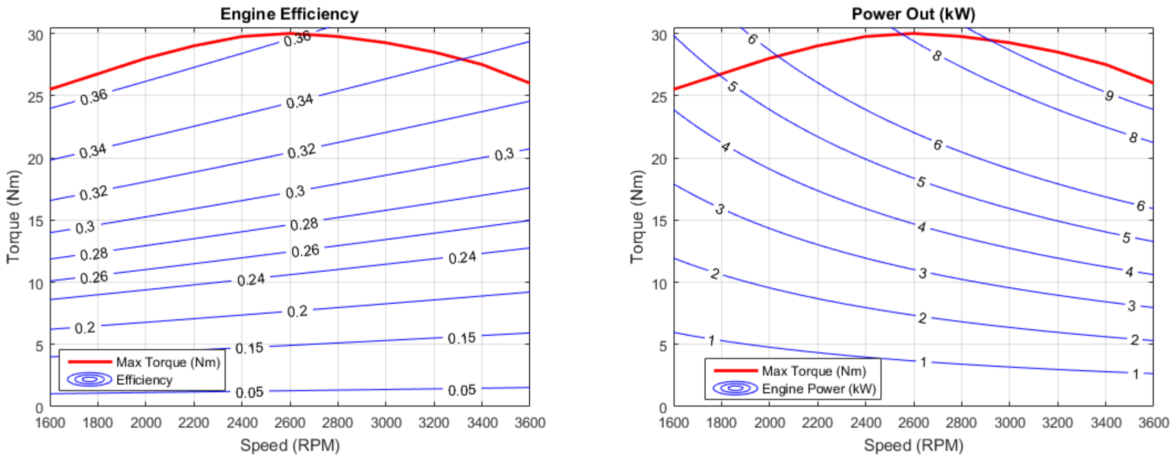
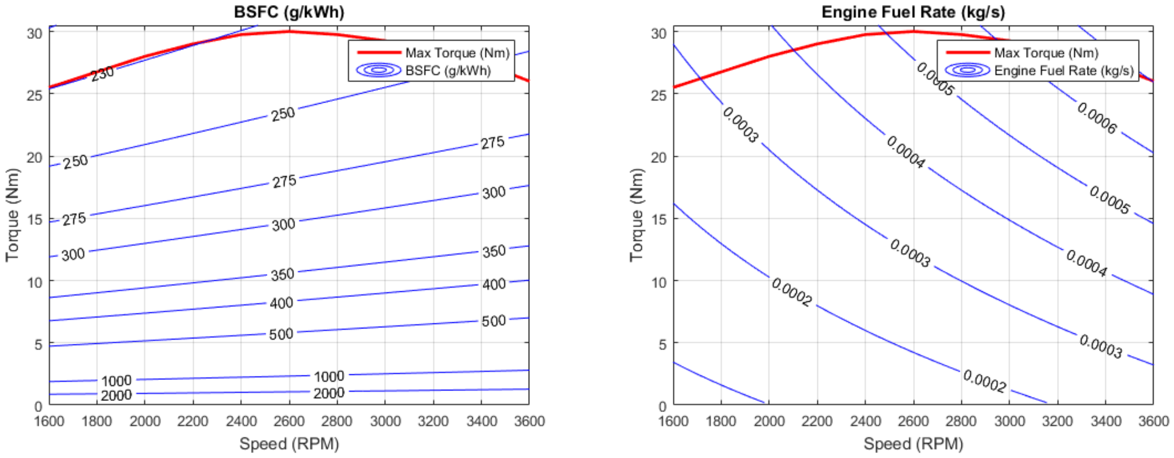


Figure 27. Friction estimate as a function of speed for Kubota Z482

Using the estimated thermal efficiency and fmep as a function of speed, the engine operation can be simulated at a variety of speed and output torques. The results of which, including the efficiency contour plot and fuel usage contour plots, can be seen in Figure 28. These are much smoother plots than those seen in Figures 4 and 18. Unfortunately, a full contour plot as seen in those figures cannot be developed through simple modeling and requires physical tests. This modeling can, however, provide a comparison of engine operation at different speeds as a proof of concept before physical tests occur.



(a) **(b)**

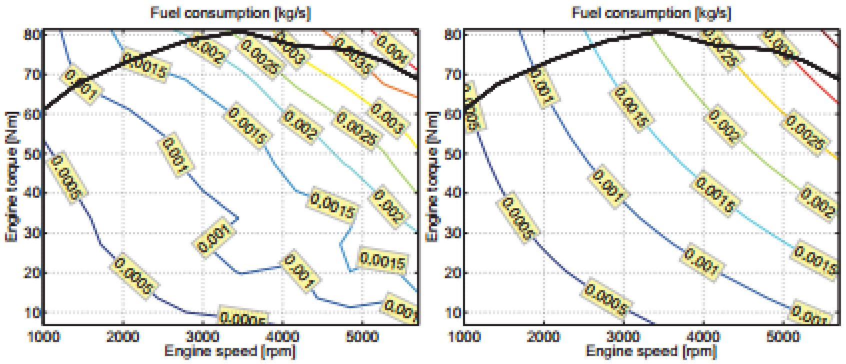


(c) **(d)**

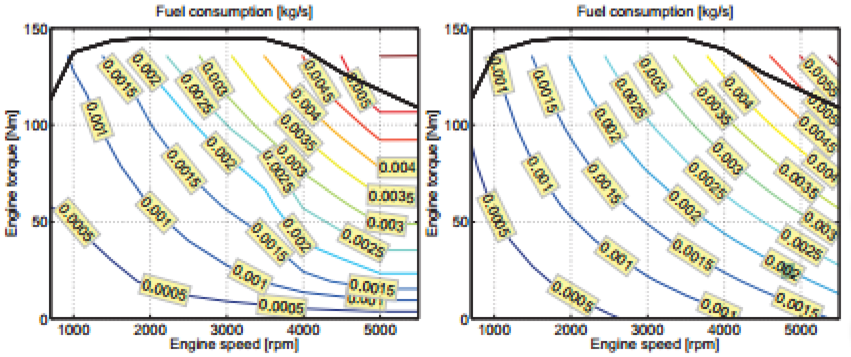
Figure 28. Contour plots for the simulated Kubota Z482 engine **(a)** Efficiency contour plot; **(b)** Brake power contour plot; **(c)** BSFC contour plot; **(d)** Fuel rate contour plot

As illustrated in Figures 5 and 19, the highest efficiency does not occur along the maximum torque line as this modeling suggests. This rises from the nonlinearities, especially at maximum power, within the engine which this model does not account for. As the only information provided by Kubota is at this maximum power condition, the actual BSFC cannot be directly compared for validation, though it is on the same magnitude as that reported by Kubota. For this reason, the max power for simulation will be taken as 90% of the max power of the engine.

In order to validate the results from this simulation, other engine simulation studies were examined to compare the results. A team at Technische Universiteit Eindhoven in the Netherlands conducted a study of different modeling and simulations methods for vehicles. Figure 29 shows their results for a backward quasi-static model and Matlab Lookup Table for two different engine sizes [43]. The team determined that the simulation method studied is a reasonable estimation for the engine operations. The fuel consumption map generated from the above modeling methods have a similar shape and are on the same order of magnitude, though the exact values cannot be compared due to the fact that these results in Figure 29 include losses through the drive train, as well as the differences in the engine size and the type of fuel used.



(a) Measured (b) Generated



(c) Measured (d) Generated

Figure 29. Fuel consumption results from the team at the Technische Universiteit Eindhoven for two engine sizes in automotive applications [43].

Through comparison of the general fuel use for the engine at max power and comparison of other published engine simulations, this paper's simulated results were taken to be a fair estimation of engine performance. Unfortunately, no information was provided by Kubota for normal operating conditions, and therefore cannot be completely validated. Maximum operating conditions cannot be used for validation due to the increased fuel consumption in a physical engine due to knock avoidance and temperature constraints which cannot be captured in this modeling. At the maximum power out, the simulated fuel use was approximately 10 - 20% lower than reported by Kubota. For more exact simulations, additional information about fuel use would be needed, either from an engine manufacturer or physical testing.

4.2 Genset Simulation

Once a reasonable engine model had been developed, a model of the genset could be developed. Only five constants are needed for generator simulation: the copper loss, iron loss, friction torque, windage loss, and constant loss constants. Since both the iron losses and fictional losses are based on the rotational speed, these constants were combined into one constant, k_i. Initial estimations for these constants can be found in Table 4.

Table 4. Initial estimates for generator loss constants [40].

Constant	Initial Value
k_c	1
k_i	0.1
k_w	0.00001
C	100 W

Unfortunately, there was no available information about the generator itself. For that reason, the generator model was developed and validation was conducted for the genset as a system, not the generator individually. Kubota reported fuel usage of the genset operating at its synchronous speed (3600 RPM) and at varying load values, listed in Table 5. Overall fuel use can be back calculated from the load power.

Table 5. Fuel usage for Kubota GL7000 genset at different loads [44].

Load Fraction	Power Output (kW)	Fuel Rate (L/h)
1	6.1	2.6
0.75	4.575	2.1
0.5	3.05	1.7
0.25	1.525	1.4

Load power can be converted into the torque necessary to power the load at the synchronous speed. This torque and speed combination can then be used to determine the losses across the generator. The input power of the generator can be found through the addition of the generator losses and output (load) power. The generator input power is also the engine output power, assuming there are no losses at the coupling. This engine output can then be used to estimate the BMEP of the engine at a given load and operating speed. This BMEP can be used in conjunction with the FMEP for the operating speed to determine the mechanical engine efficiency using Equation 25. The overall efficiency can then be calculated using Equation 15 and the realistic thermal efficiency value of 50%. This engine efficiency can be used to determine the fuel rate of the engine. A parametric study was conducted to find a suitable set of constants. The final constants chosen were those which provided fuel usage for all load levels within 5% of those reported by Kubota. The fuel usage and corresponding Kubota reported fuel usage can be found below in Table 6, and the final set of constants can be found in Table 7. A contour map of the generator can be seen in Figure 30. The maximum simulate efficiency of this generator is 73%

Table 6. Simulated fuel rate of the Kubota GL7000 compared to reported values. All values are within a 5% of the reported values.

Load Fraction	Kubota Reported Fuel Rate (L/h)	Simulated Fuel Rate (L/h)	Percent Difference

1	2.6	2.48	4.45
0.75	2.1	2.09	0.64
0.5	1.7	1.72	1.16
0.25	1.4	1.37	2.06

Table 7. Final generator constant values used for simulation.

Constant	Final Value
k_c	2
k_i	0.5
k_w	0.000025
C	50 W

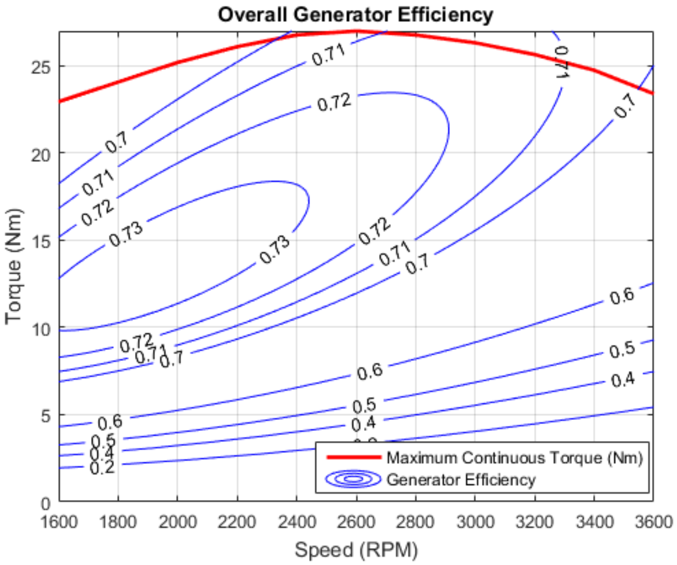


Figure 30. Generator efficiency contour plot. The maximum efficiency is 73%.

Due to the minimal error between the reported Kubota fuel usage at different loads and the simulated results, the overall genset model was assumed to be an acceptable estimation. A contour plot of the overall genset efficiency can be found below in Figure 31.

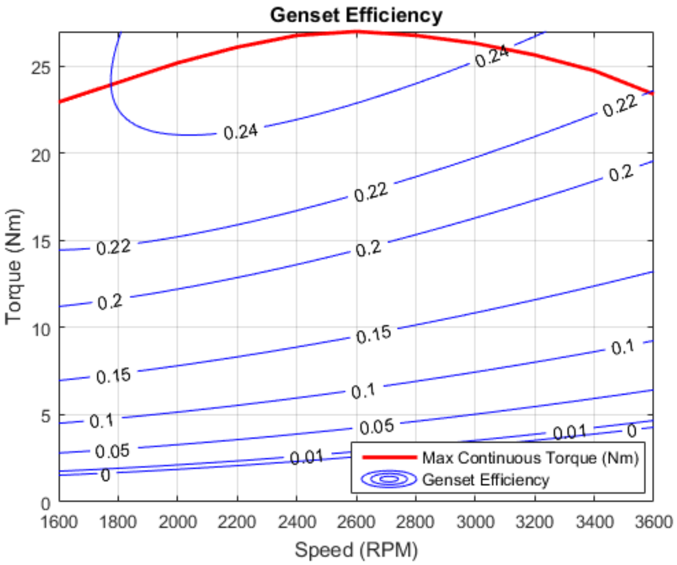


Figure 31. Simulated efficiency, or the relationship between the output power from the generator to the input power from fuel into the engine, contour map for the Kubota GL7000.

The above engine map can be used to determine the efficiency, and subsequently the fuel use, of the genset at different load conditions. The maximum efficiency is approximately 24% between 1800 and 2800 RPM. The maximum efficiency for a given speed occurs along the maximum continuous torque line.

4.3 Simulation of Genset at Varying Operating Speeds

When a genset is connected to the grid, it must run at a speed to produce 60 Hz. For GL7000 generator used, this speed is 3600 RPM. As can be seen through the efficiency contour plot shown in Figure 28b, this synchronous speed, does not relate to the point of highest efficiency for the engine; at max power, maximum efficiency (lowest BSFC) occurs at approximately 2400 RPM. While the engine typically does not operate at maximum power, the trend continues to lower power outputs as well. This condition arises due to the nature of power curves. While an engine operating at the same torque will be more efficient at lower speed, the lower speeds relate to lower power output. Therefore, as speed increases at the same power output, torque decreases, and the engine transitions to a lower efficiency. This concept is expressly illustrated in Figure 32, which shows the genset efficiency for a 3 kW load at various speeds. This simulation is for a DC load and does not include losses of a rectifier or inverter. At a constant load of 3 kW, the engine operates more efficiently at 1800 RPM, with a 10% decrease in overall efficiently between 1800 RPM and the synchronous speed of this genset, 3600 RPM. This relates to using 0.12 gallons less of fuel over an hour of operation, or 3.15 gallons less over 24 hours of continuous operation.

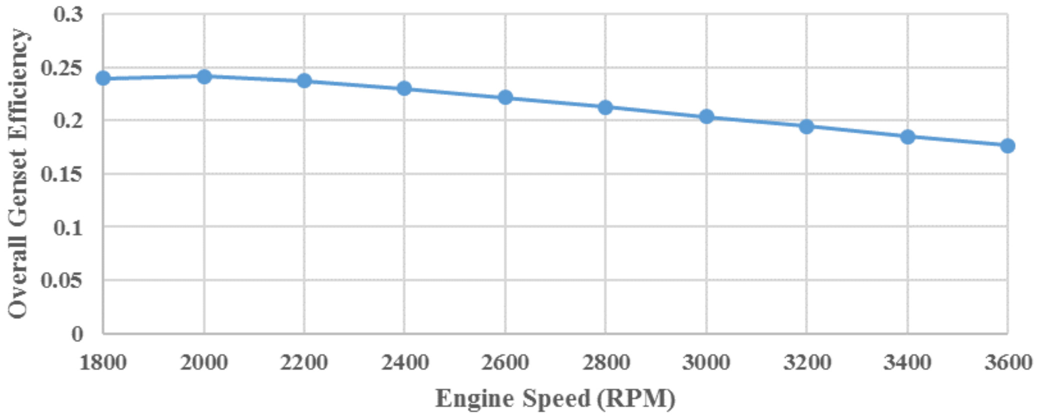


Figure 32. Overall genset efficiency for the simulated genset with a 3 kW load.

Decreasing the engine speed will result in more efficient fuel operation, but the overall system efficiency is limited by constant operation. The addition of an energy storage device could provide for a more efficient system.

4.4 Battery Use at Varying Operating Speeds

When trying to increase the efficiency of a genset, one way to achieve this goal is to operate the system at a lower speed, as illustrated in Section 4.3. This action, however, diminishes the power available by the system, and the genset will therefore need to be oversized to achieve the necessary power at a lower speed. The power and fuel efficiency contour plots shown in Figure 27 illustrate that diesel engines, and subsequently, diesel gensets, operate more efficiently at a given speed at higher powers. This concept demonstrates a second way to increase the efficiency of the genset: operation of the engine at a higher power at lower speeds.

While it is possible to add so called “dump loads” to a system to operate it at a more efficient point, but there will be power produced not applied to the load, resulting in a loss in efficiency. This method of adding a dump load is not ideal. The more conventional method is to add a battery to the system. With the addition of a battery, the engine will operate to power the load, as well as charge the battery at a given rate. Such systems are described in detail in Section 2.2.

A battery pack can be integrated into the genset model, and its operation can be simulated in a similar manner. The battery was modeled as two, 12 V batteries in series with a capacity of 110 Ah each. This configuration is common for portable gensets equipped with reserve batteries. A cycle charging dispatch method was chosen, charging the battery to ensure a SOC between 30 and 90%. The 30% minimum was chosen to safeguard against over-discharging. The 90% maximum was chosen to guarantee the charging mode stayed in the constant current area, so trickle charge simulation was not necessary. The system was initially simulated at 1800 RPM at different loads and charging rates, the results of which can be seen below in Table 8. The base simulation time was two days (2880 minutes), though this time was adjusted for each iteration to ensure that the simulation ended with a fully discharged battery. At 1800 RPM, the maximum power out of the generator was estimated at about 3 kW, so the sum of the load and battery charging must be less than this value. As can be seen, the addition of a battery pack can greatly increase the efficiency of the system, with an increase of almost 10% for a 1 kW load with 2 kW charging, which has an efficiency of 24%, when compared to the 1 kW load, which has an efficiency of 15%. The major improvement with the addition of the battery comes with less engine on time, which decreases with higher charging power.

Table 8. Simulation results for the Kubota GL7000 genset at 1800 RPM for varying loads and battery charging powers.

Load (kW)	Battery Charging (kW)	Efficiency	Engine Time On (min)	Charge Time (min)	Discharge Time (min)	Total Simulation Time (min)
1	0	0.156	2880			2880
2	0	0.221	2880			2880
3	0	0.242	2880			2880
1	1	0.221	1410	82	82	2821
2	1	0.242	1886	82	41	2829
1	2	0.242	965	42	84	2896

An energy balance can also be useful to determine where the losses occur within the system. The total energy into the system is the energy within the diesel added to engine. The energy stored within the battery must also be considered. The energy into and stored in the system be seen in Table 9. The energy out of the system is load can be seen in Table 10, and includes the base load and battery charging, the energy lost through the engine, and the energy loss through the generator. The energy balance does match. As expected, the largest losses occurred over the engine.

Table 9. Energy added to and stored within the system.

Energy Added to and Stored in System	
Component	Energy (kWh)
Engine/Diesel Fuel	199.16
Total	199.16

Table 10. Energy leaving the system. This is equal to the energy added to and stored within the system, which is to be expected.

Energy Out of System	
Component	Energy (kWh)
Engine Losses	128.34
Generator Losses	22.56
Load	48.27
Total	199.17

The same simulation can be done at varying operating speeds. To compare these results, the genset was simulated at 2600 RPM and 3600 RPM, the results of which are shown below in Tables 11 and 12. The maximum total load for the genset is 5 kW at 2600 RPM and 6 kW for 3600 RPM. As can clearly be seen in these results, as with those in Table 8, the efficiency of the system increases with the addition of a battery pack while the engine on time decreases as charging power increases. System efficiency increases the most for a small load and high power battery charging.

Table 11. Simulation results for the Kubota GL7000 genset at 2600 RPM for varying loads and battery charging powers.

Load (kW)	Battery Charging (kW)	Efficiency	Engine Time On (min)	Charge Time (min)	Discharge Time (min)	Total Simulation Time (min)
1	0	0.105	2880			2880
2	0	0.169	2880			2880
3	0	0.210	2880			2880
4	0	0.236	2880			2880
5	0	0.250	2880			2880
1	1	0.169	1410	82	82	2821
2	1	0.210	1886	82	41	2829
3	1	0.236	2182	84	28	2910
4	1	0.250	2266	84	21	2833
1	2	0.210	965	42	84	2896
2	2	0.236	1435	41	41	2870
3	2	0.250	1722	42	28	2870
1	3	0.236	728	28	84	2913
2	3	0.250	1148	28	42	2870
1	4	0.250	579	21	84	2836

Table 12. Simulation results for the Kubota GL7000 genset at 3600 RPM for varying loads and battery charging powers.

Load (kW)	Battery Charging (kW)	Efficiency	Time On (min)	Charge Time (min)	Discharge Time (min)	Total Simulation Time (min)
1	0	0.067	2880			2880
2	0	0.116	2880			2880
3	0	0.154	2880			2880
4	0	0.183	2880			2880
5	0	0.206	2880			2880

6	0	0.223	2880			2880
1	1	0.116	1410	82	82	2821
2	1	0.154	1886	82	41	2829
3	1	0.183	2182	84	28	2910
4	1	0.206	2266	84	21	2833
5	1	0.223	2379	85	17	2855
1	2	0.154	965	42	84	2896
2	2	0.183	1435	42	42	2870
3	2	0.206	1722	42	28	2870
4	2	0.223	1890	42	21	2835
1	3	0.183	728	28	84	2913
2	3	0.206	1148	28	42	2870
3	3	0.223	1420	28	28	2841
1	4	0.206	567	21	84	2836
2	4	0.223	946	21	42	2836
1	5	0.223	476	17	85	2857

Ultimately, the efficiency of the system dramatically improves with the addition of a battery pack. For example, at 3600 RPM, the efficiency for a 1 kW load increases from an efficiency of around 6% to an efficiency of approximately 22% when a battery is charged at 5 kW (total load of 6 kW). The actual increase in overall efficiency is greatly dependent on the situation. For example, the addition of a battery which is capable of being charged at 5 kW will likely be too heavy and expensive to be incorporated into the system. A more feasible charging power is 1 kW. Such a charging power was simulated with a 3 kW load to compare to the simulation illustrated by Figure 32. The minimum speed for this operation is 2600 RPM. Below this speed, a charging power of 1 kW would not be possible. The results of this simulation can be seen in Figure 33. The maximum efficiency of this simulation is approximately 24% at 2600 RPM. Operation under these conditions allows for 5.5 gallons of diesel saved when compared to operation at 3600 RPM with 1 kW battery charging, and 7.75 gallons when compared to the normal operation at 3600 RPM with no battery.

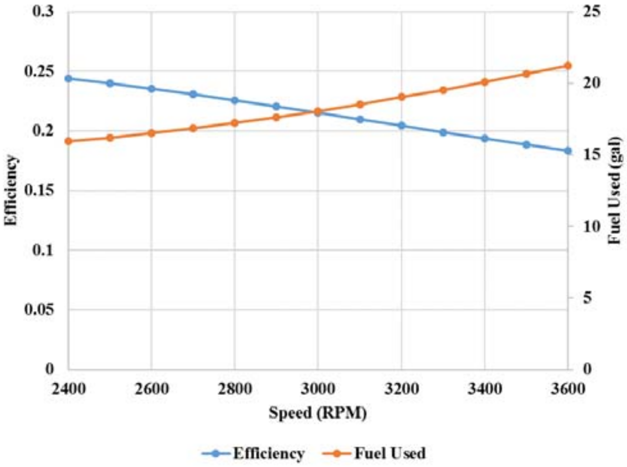


Figure 33. Operation at different speeds for a 3 kW load with 1 kW battery charging.

To better implement a genset – battery system, knowledge of the genset "mission" is necessary to ensure the optimal design. For example, some situations, such as those for the military, may prefer a system with more "quiet", or engine off, time, and would sacrifice efficiency to achieve this goal. If weight is a concern, operating at a condition which is not peak power to achieve a higher efficiency is not optimal because the engine would be oversized for a specific load. The simple addition of a battery pack to achieve higher efficiency of the system overall can dramatically increase the price. Mission awareness, especially load knowledge, is key to ensuring an optimal design.

4.5 System Design

A diesel genset for remote power generation can be designed in order to operate at its most efficient point, which corresponds to the lowest fuel consumption. Knowledge of the load must be known in order to correctly size all the components. For example, for a constant load of 5 kW, the Kubota GL7000 could be chosen with the operating speed set at 2600 RPM in order to optimize efficiency. If the load requirement is 6 kW, the operating speed should be chosen at 3600 RPM in order to optimize efficiency.

A battery pack can also be incorporated into the design of a genset. The battery pack to be used should be known in order to effectively incorporate it into a system. The battery pack charging capacity will be used in order to ensure the system operates at the most efficient speed. For example, with a 5 kW load, a battery could not be incorporated into the Kubota GL7000 operating at 2600. This is because the entirety of the genset output power would be powering the load. However, a battery could be incorporated into the system if it operated with a 4 kW load at 3600 RPM. The battery could be charged with the remaining 2 kW available from the genset at this speed, if the battery pack capacity allowed. If not, a lower operating speed should be chosen to optimize efficiency. The operation of the genset with a 4 kW load and 2 kW battery charging at

3600 would result in an efficiency of 22%, higher than the efficiencies for a 4 kW load at both 2600 and 3600 RPM, 23% and 18% respectively.

Knowledge of the load, as well as knowledge of the equipment to be used is essential to determine the optimal operating conditions for a diesel genset.

Chapter 5 Summary

Chapter 5.0 Chapter Overview

This chapter details final conclusions which can be made from the study conducted. Conclusions will be made about the modeling and simulation conducted, operating efficiency for a diesel engine, and the future work related to each.

Chapter 5.1 Modeling Conclusions and Next Steps

Chapter 3 details the modeling, with a focus on efficiency, of the diesel engine, generator, and overall genset. The validation in Sections 4.1 and 4.2 illustrates that these models provide reasonable estimations of system performance with respect to output power and fuel consumption for various operating speeds. Unfortunately, these models cannot capture many of the nuances of system operation, specifically for the nonlinearities of the engine. These nonlinearities account for less than 5% of the overall losses within the engine, and were deemed insignificant for this analysis.

In order to capture these nuances and create a better model, physical testing should be conducted for the engine of use. While a full engine map, such as those shown in Figures 5 and 22, may not be possible to obtain, fuel consumption for normal operating conditions (80% of the maximum available torque) at multiple speeds could improve model accuracy. Additional testing should be conducted with the generator of use as well. Estimation of the loss coefficients can provide an approximation for efficiency, but will again provide for imprecise simulation.

Chapter 5.2 Genset Operation for Increased Efficiency

The operating speed of the engine has a large influence on the efficiency of the engine. Gensets used for remote power generation are currently designed to operate at the fixed grid frequency, even though this function may not be necessary. Fixed speed operation also limits the power output of the generator. Operating at a fixed speed results in the genset increasing or decreasing fuel consumption in order to meet a varying load. As shown in Figure 31, only high load conditions result in maximizing efficiency. Additionally, for fixed speed operation, the engine will be oversized, when operating at 1800 RPM, or the engine will operate inefficiently at low loads, when operating at 3600 RPM. By allowing the system to operate across a range of speeds which do not produce 60 Hz, the efficiency of the engine can be optimized, as shown in Figure 32.

While decreasing the engine speed increases the efficiency, lower speed operation will also decrease the power out, requiring an oversized engine. As can be seen in Table 8 – 10, low speed operation will increase the overall efficiency for a given load, but the system will be limited on the load it is able to power. For this reason, there should be a reasonable knowledge of the load for appropriate engine sizing when designing a system. This knowledge would allow for the system to be sized for maximum efficiency at the required load at the chosen, fixed speed. For maximum efficiency, the engine and generator should be jointly considered and sized appropriately, and the fixed speed should be chosen based on combined efficiency, not just that of the engine. The use of a CSC rectifier system should be used to ensure that the maximum power from the genset is transferred to the load. If such a rectifier is not available, a PWM rectifier should be used, though would result in a lower efficiency.

Variable speed generators were discussed in Section 2.1, but a simulation of such a system was not conducted. Variable speed generator simulations are the next step for this study. Specifically, the efficiency of a variable speed genset should be compared to that of the non-grid connected, fixed speed gensets that were investigated. The non-grid connected, fixed speed gensets would be relatively simple to size and implement for a fixed load application. They would limit efficiency for a variable load, similar to that of a grid-connected generator. When controlled correctly, one can speculate that variable speed operation would allow the genset to operate at its most efficient point for a given load, regardless of speed.

The addition of a battery is essential to increasing the efficiency of a system, regardless of fixed or variable speed. As detailed in Section 4.3, a battery can dramatically increase the efficiency of a system, and will allow for time where the engine is not running. This battery, as with the engine and generator, must also be appropriately sized. The battery can be charged with any remaining power that can be generated by the system in order to operate at the maximum efficiency for a given speed, but care must be taken to ensure that the battery can be charged at such a rate. As detailed in Section 2.2, fast charging can be dangerous for the battery. A dispatch analysis should also be conducted for the specific task of the genset to ensure that the optimum charging strategy can be applied. If applying to a variable speed generator, an efficiency analysis should be conducted to determine the most efficient operation strategy. These strategies include operation at a higher power, lower efficiency point of the generator in order to charge the battery faster, or operation at a lower power, higher efficiency point of the system. The highest efficiency of the simulated engine occurred when operating at 2400 RPM, with a 1 kW load and battery charging at 3 kW. The addition of a battery allows for the genset to operate at its maximum efficiency for a wide variety of loads, and will allow for periods of time where the system is not running. Analysis of the specific load conditions should be done in conjunction with component selection in order to choose the most efficient operating conditions.

Chapter 5.3 Summary

This study of diesel gensets and their operating set points can be generalized as follows:

1. Grid connectivity, or the operation at a 60 Hz output, limits the performance of the system. Operation of a two pole generator at 3600 RPM will result in low efficiency at low loads. Operation of a four pole generator at 1800 RPM will result in a limited power output. The efficiency can be optimized for a single load. Maximum efficiency will not be reached for varying loads.

2. Detailed engine and generator efficiency maps are necessary in order to accurately model a system.

3. Detailed knowledge of the load is necessary in order to accurately size a genset.

4. In order to achieve the maximum power transfer to a DC load, a CSC rectifier should be used.

~~6.~~5. The addition of a battery will increase the efficiency of a system.

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