Intelligent Control of Multiple Small Electric Generator Sets

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Synopsis

Historically, ships have relied on large diesel and gas-turbine generators to supply electrical power. The loads deployed have been largely continuous and predictable allowing the generators to be run efficiently while maintaining acceptable power quality. Future electrical loads may operate with much less predictability and simply scaling up the size or even the number of large generators may not be the most effective way to meet this demand. Instead, it could be much more feasible to install more smaller generators that can be actively controlled according to priorities set by the power system operator. If controlled properly, it is possible to optimize efficiency, reduce maintenance costs, and increase usable life. Integration of energy storage may provide ride through support required to bring up additional generation in the event of an outage. In the work documented here, intelligent control is being used to study this approach for optimizing multiple small generators.

Keywords: Microgrid; Medium-Voltage Power Distribution; Power System Control; Power Electronics; Energy Storage

1. Introduction

Historically, ships have relied on large diesel and gas-turbine generators to supply power throughout a ship. Multiple generator sets are usually installed, sufficient such that even if generators are lost, there is still enough capacity to maintain power system reliability and operability of critical loads. When large generators are lightly loaded, it is bad for their efficiency and lifetime, leading to higher fuel costs and more frequent maintenance needs. Traditional shipboard loads have been mostly continuous and predictable allowing the large generators to be run in a way that maintains sufficient power quality. Future ships will demand more from their electrical power sources than ever before (Doerry 2006, Doerry 2010, Thongam 2013, NGIPS 2007, Cohen 2015, Cohen 2017, Cohen 2016, Cohen 2014, Wong 2016, Wetz, 2014, Dodson 2019, Sanchez 2017). This stems from the desire to install electrical propulsion systems as well as transiently operated loads that will suddenly introduce unexpected periods of elevated and decreased load, respectively. This operation imparts increased stress on diesel and gas-turbine engine-generator sets and can significantly impact power quality, efficiency, and mean-time-between failure (MTBF), among other factors. Also, it is more difficult to source replacement parts for these larger generators as they are more niche in their use, contributing to longer outages whenever a part needs to be replaced. In addition to that, large generator replacements from different manufacturers may not adhere to the same dimensional specifications due to a lack of standardization and commercial availability.

Rather than continue to increase the number of larger generators installed to meet the new load, it may be more feasible to install many smaller generators that can be brought up and operated only as needed. When not needed, these smaller generators can be left off, reducing wear and tear, reducing maintenance costs, and increasing usable life. Replacing parts, and even generators themselves when needed, is much easier and more cost effective when smaller generators are used due to increased commercial acceptance and availability. This is an approach that has been adopted by some in the nuclear power industry where it is critical to always ensure that backup power is available (Framatome 2022). Regulating the load supplied by individual engine-generator sets connected on a point of common coupling (PCC) is difficult, but if instead the generators are rectified using power electronic converters before being connected onto a common DC bus, they become much easier to regulate and control. This is an approach being studied here.

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Hypothetically, instead of installing two – 2 MW generator sets to meet a 2 MW shipboard power load, assuming twice the required capacity is installed to ensure operability if one of the larger generators is lost, 16, 250 kW generator sets could be installed to achieve the same possible capacity. However, since the likelihood of multiple smaller generators going down simultaneously is very low, fewer smaller generators are needed to maintain the required operability. Further, when the expected load is low, a smaller number of generators can be run that meet the reduced load with redundancy still online that totals less than the full power capability of the power architecture. This allows generator sets to be kept at rest, thus reducing their wear and tear, and increasing their MTBF. Active control of the online generators enables power quality to be monitored or protected and efficiency to maximized. Rotating through generator sets that are in an online and resting state may be advantageous to long term maintenance costs. All these factors and how they are controlled depend heavily on the controller architecture, something also being studied here. Each operator or operational scenario may have a different perspective on what control parameters should be optimized and thus flexibility in the controller allows this architecture to meet the needs of each individual situation.

Because it takes time to spin up a generator, it is still a requirement to have more generation always available to maintain load if a generator goes down. Smaller generators will have a slightly faster spin up time, another benefit they afford. Having energy storage installed to maintain the load through the spin up time is an option that further reduces the need for extra generators to be running. The use of energy storage is something that will be studied in the future but not until a framework has been established considering only engine-generator sets.

Here, a simulation framework has been assembled using Simulink to study the pros and cons afforded by a power system that uses many smaller generators in place of a few larger generators. Initially, operational metrics of power quality, efficiency, and MTBF are being used as control variables. An optimal control (OC) architecture, costing these three operational metrics, is being studied initially. A fuzzy logic controller (FLC) is also being considered to help mitigate the effects of transients. The work completed to date along with a few results obtained will be presented here.

2. Background

There is debate surrounding the architecture of next generation shipboard power systems. While some may argue to keep things the way they have always been and simply install additional generation to meet the new load demand, there are many proposing that a new interconnected network of distributed AC and DC generation sources be employed. A shipboard architecture proposed by Doerry (Doerry 2006), seen in Figure 1, breaks the ship's power system into zones, each of which has its own sources, loads, and power electronic converters, respectively. This is an attractive architecture that should be considered for any ship application. Interconnection of zones is achieved using a dual medium voltage (MV) DC bus and bi-directional power converters that allow zones to share power amongst each other. Though MVDC has many attractive features, power converters that work at MVDC are still early in their technological development and this makes implementation near term too ambitious. Similar architectures have been proposed utilizing a dual MVAC bus (Doerry 2010), seen in Figure 2. Transformers allow the MVAC bus to be stepped down and power electronics are technologically mature to regulate AC voltages at least as high as 12.8 kV. In either architecture, there are distributed electrical generators installed. Replacing larger generators with 'generator units' made up of multiple smaller generators, like that seen in Figure 3, may be advantageous in the ways described earlier.

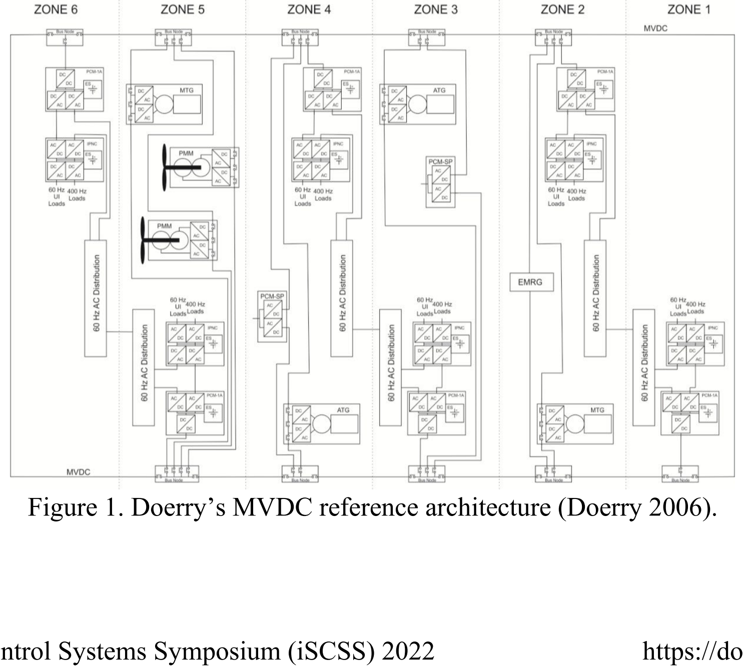


Figure 1. Doerry's MVDC reference architecture (Doerry 2006).

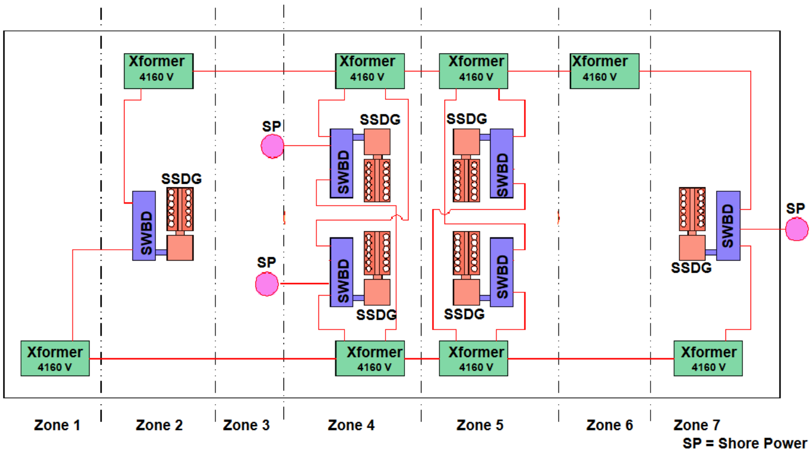


Figure 2. Doerry's MVAC reference architecture (Doerry 2010).

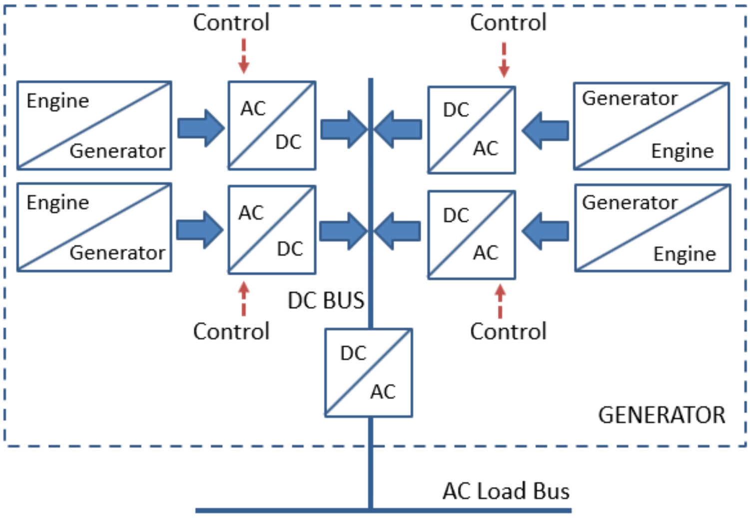


Figure 3. Single generator unit comprised of four smaller generators.

Monitoring voltage, current, and power throughout the power system and using those measurements to actively control each respective element is critical to the success of all the architectures shown in Figures 1 – 3. In smaller ships, where zonal architectures don't make sense, the utilization of the controllable 'generator units' shown in Figure 3 brings about the same benefits. In Figure 3, each individual generator is controlled by modulating the power converter between it and the DC PCC. A voltage regulator added onto an engine-generator set could be used to adjust its field current and regulate its output voltage, but typically by only increasing or decreasing a few percent of its nominal voltage with variable response times. Externally connected AC/DC and DC/DC power electronic converters can be used to regulate a generator's output power more widely onto a common DC bus. The focus of the work described here is specifically on monitoring and controlling each individual generator within a 'generator unit', not on the broader power system.

The control algorithms used to provide reference signals to the power electronic converters is another factor that will play a large role in the success of the proposed generator unit architecture. Optimal Control (OC) and Fuzzy Logic Control (FLC) architectures are being studied. OC considers several variables that are input to the controller that are in terms of cost functions. As the name implies, it assumes that it 'costs' something to achieve the performance the function is defining. The OC algorithm seeks to optimize system performance by minimizing the total costs and maximizing the performance index. A classic example of an OC problem is Zermelo's Problem (Bryson 1975). The problem deals with finding the optimal control of a boat to travel across a body of water faced with strong currents and winds. The cost associated with the problem is the time to reach the destination and the objective is for time to be minimized. Solutions to this problem, and many others, apply calculus of variations to find the optimal control. The solution method relates multiple performance metrics of a system to achieve an output response. The system metrics can be used to construct a cost function that will find the optimal control. A relationship between the control and cost function is shown below,

$$J(t_0) = \phi\left(x\left(t_f\right), t_f\right) + \int_{t_0}^{t_f} L(x(t), u(t), t)dt$$

where $J(t_0)$ is the cost function, ϕ is a function that gives importance to the final state and final time, and L is a function that depends on the states and control input as they evolve from initial time t_0 to final time t_f. Finding the optimal control ends up solving for the control input used to minimize the cost function. The goal here is to define cost functions for the power quality (voltage deviation), generator efficiency, and generator MTBF, among other properties yet to be defined. In Figure 4, example cost functions defined for generator efficiency, left, and bus voltage deviation, right.

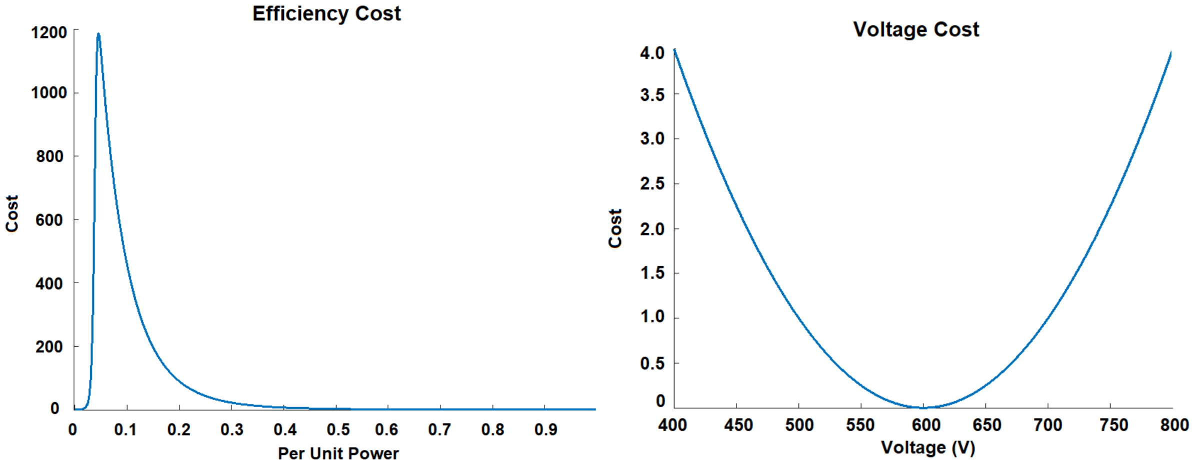


Figure 4. Cost functions used to define the cost of generator efficiency (left) and voltage deviation (right).

FLC employs an if-then rule-base with mathematical fuzzification and defuzzification to achieve an expert response with a digital controller's speed and efficiency. In other words, it behaves as a human would if they had expert knowledge on the desired behaviours of the system. Just as humans think differently, a FLC can be made to think differently based off the rule set and weighting they are provided. Fuzzy logic control has been used in many applications such as (Sanchez 2017, Semwal 2015, Wu 2010, Yu 2008, Ross 1995). (Semwal 2015) developed an intuitive FLC based learning algorithm which was implemented to reduce intensive computation of a complex dynamics such as a humanoid. Some, such as (Sanchez 2017) have utilized FLC to drive a hybrid energy storage module (HESM), but in their case, they used the controller to eliminate the need to constantly calculate resource intensive Riccati equations to assist in choosing gains for an adaptive Linear-Quadratic Regulator controller. Others, such as (Wu 2010, Zu 2008) developed an energy-based split and power sharing control strategy for hybrid energy storage systems, but these strategies are focused on different target variables such as loss reduction, levelling the components state of charge, or optimizing system operating points in a vehicular system. Fuzzy systems typically achieve utility in assessing more conventional and less complex systems (Semwal 2015, Ross 1995), but on occasion, FLC can be useful in a situation where highly complex systems only need approximated and rapid solutions for practical applications. A FLC can be particularly useful in nonlinear systems that shift between different operational states. One key difference between crisp and fuzzy sets is their membership functions. The uniqueness of a crisp set is sacrificed for the flexibility of a fuzzy set. Fuzzy membership functions can be adjusted to maximize the utility for a particular design application. The membership function embodies the mathematical representation of membership in a set using notation Ω_i, where the functional mapping is given by $\mu_{\Omega_i}(x) \in [0,1]$. The symbol $\Omega_i(x)$ is the degree of membership of element x in fuzzy set Ω_i and $\mu_{\Omega_i}(x)$ is a value on the unit interval which measures the degree to which x belongs to fuzzy set Ω_i. While there are many different types of Fuzzy Inference Systems (FIS) for a FLC, that being type-1 or type-2 and Mamdani or Sugeno, the one being used for this study is a type-1 Mamdani FIS due to it being better suited for human input and its more easily interpretable rule base. A Sugeno FIS may be explored in the future due to its advantages in working with optimization techniques, but not until a full framework has been made. Figure 5 shows some generic membership functions that could be used to define a FLC.

Rule sets are being defined analogous to the costs defined in the OC method, including power quality (voltage deviation), generator efficiency, and MTBF. There is not presently a good standard for DC power quality to reference in the development. MIL STD-1399 (MIL-STD-1399 2018) outlines the power quality constrains for an AC system on a naval vessel but since it is only interested in the load bus, which is DC here, it is hard to apply. A membership function is defined to determine the model's response when the DC bus deviates from that required to maintain sufficient power quality. Generator efficiency is defined referencing published curves documenting a generator(s) efficiency as a function of the power it is supplying. A MTBF curve is one that is difficult to define as it varies so significantly on how the generator is run and its history of operation. The MTBF rule set is generically defined in the work to date with the assumption that generator manufacturer(s) will be able to provide this information for their specific generator(s) in the future. There are many different factors that affect MTBF which may result in a more complex group of membership functions being used in the future. The model is not ready to accurately respond to all these rule functions just yet, but a framework is in place and incremental progress is being made each month. That progress will be documented in the sections that follow. A hypothetical explanation of the rule sets being used currently is shown in Figure 6.

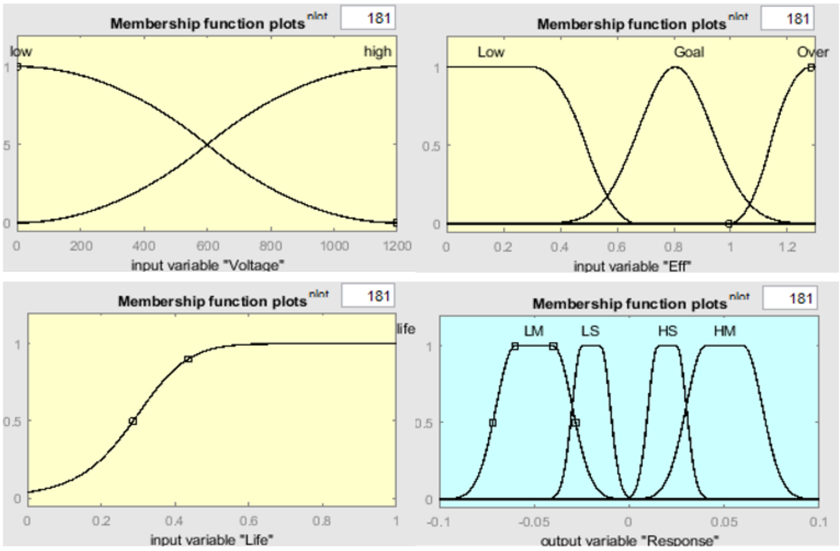
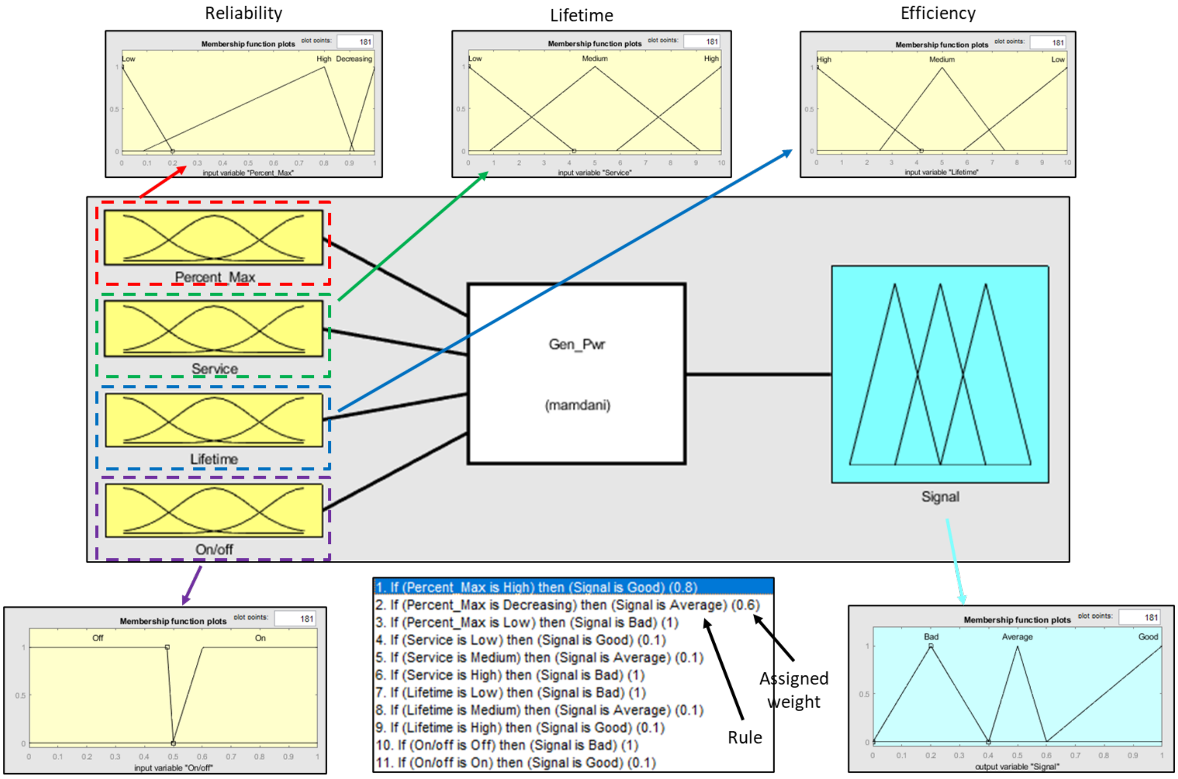


Figure 5. Example fuzzy membership functions.



1. If (Percent_Max is High) then (Signal is Good) (0.8)
2. If (Percent_Max is Decreasing) then (Signal is Average) (0.6)
3. If (Percent_Max is Low) then (Signal is Bad) (1)
4. If (Service is Low) then (Signal is Good) (0.1)
5. If (Service is Medium) then (Signal is Average) (0.1)
6. If (Service is High) then (Signal is Bad) (1)
7. If (Lifetime is Low) then (Signal is Bad) (1)
8. If (Lifetime is Medium) then (Signal is Average) (0.1)
9. If (Lifetime is High) then (Signal is Good) (0.1)
10. If (On/off is Off) then (Signal is Bad) (1)
11. If (On/off is On) then (Signal is Good) (0.1)

Figure 6. Hierarchy of the FLC rule sets and a generator model.

OC and FLC will most likely be used together to optimize the ‘generator unit.’ One such scheme employs the use of a FLC to determine the operation of the generation units during a transient event to improve short term power quality, then using the OC as the steady-state controller that determines the optimum generator distribution. This would allow the OC to run at a slower rate, decreasing computational power requirements.

3. Simulink Model Development and Experimental Results

Generator Model

The Simulink modelling environment is being used in all the work performed here. It is intended to be flexible so that the user will be able to easily change the electrical and mechanical properties of the eventual generator(s) that will be simulated as well as the OC cost functions and FLC rule sets that define the controller's response. To date, individual components of the model have been worked on with varying levels of success. Connecting each component into the full system is the next step on the model development flow.

The generator being modelled is an example provided in the Simscape – Electrical toolbox. The fidelity of the generator and its ability to be adjusted to represent different physical hardware is important. The 'Marine Full Electric Propulsion Power System' example is being used (MATLAB 2013). The example contains a model of a 5 MVA diesel generator as well as a 30 MVA gas turbine generator. Both have an integrated automatic voltage regulator (AVR), exciter, governor, and alternator. The diesel generator model is being used and its parameters have adjusted to rate it for 480 VAC and 250 kVA. Figure 7 shows the generator model and a plot of its voltage sag and surge when it is transiently loaded at increments of 50 kW up to 300 kW. During and after each transient event, the generator voltage is allowed to stabilize before it is unloaded or loaded again. The lower right image in Figure 7 also plots the voltage deviation limits defined in MIL-STD-1399. Notice that under transient load conditions of 250 kW and 300 kW, the generator's voltage sag and surge exceed the limitations of MIL-STD-1399, something the controller will aim to prevent. Figure 8 shows a Simulink model where a single generator unit is fed into a transformer with a 1:1 ratio to eliminate triple harmonics seen by the generator. The transformer output is rectified using a simple three-phase diode rectifier to create a ~600 VDC bus that is next fed into an average value DC/DC converter model. The converter is controlled using a dual PD controller that regulates its voltage and current. Those controls will eventually be supplied by either the OC, FLC, or combination of the two. Figure 9 contains an image of a Simulink model in which single generator assemblies have been combined into a 'generator unit' feeding a common DC bus. No results from these simulations will be presented here since the controls are not yet developed but it serves as an introduction to where this work is going.

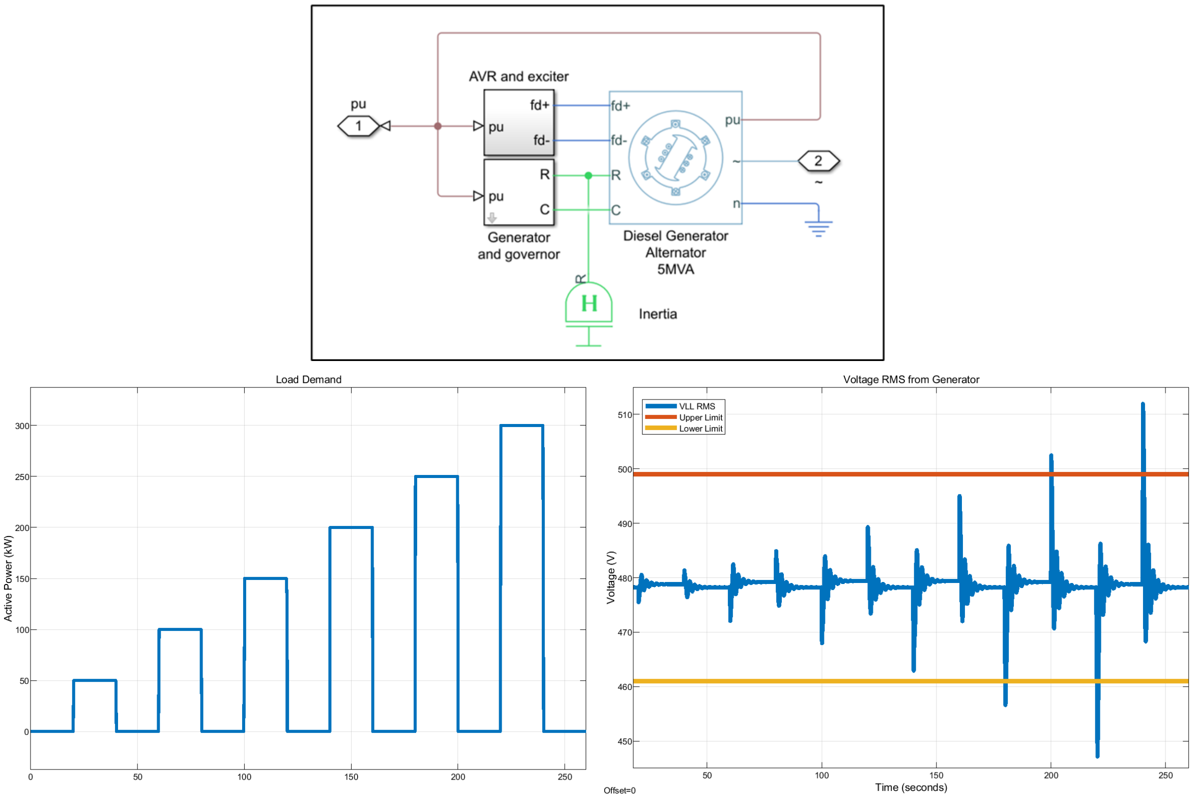


Figure 7. MathWorks 250 MVA diesel generator model (above), transient load profile (bottom left), and generator output voltage (lower right) that results.

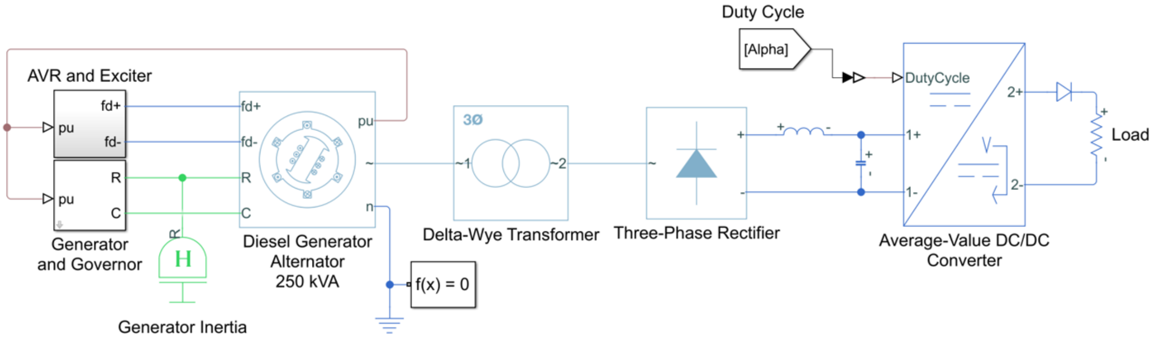


Figure 8. Single AC Generator Model.

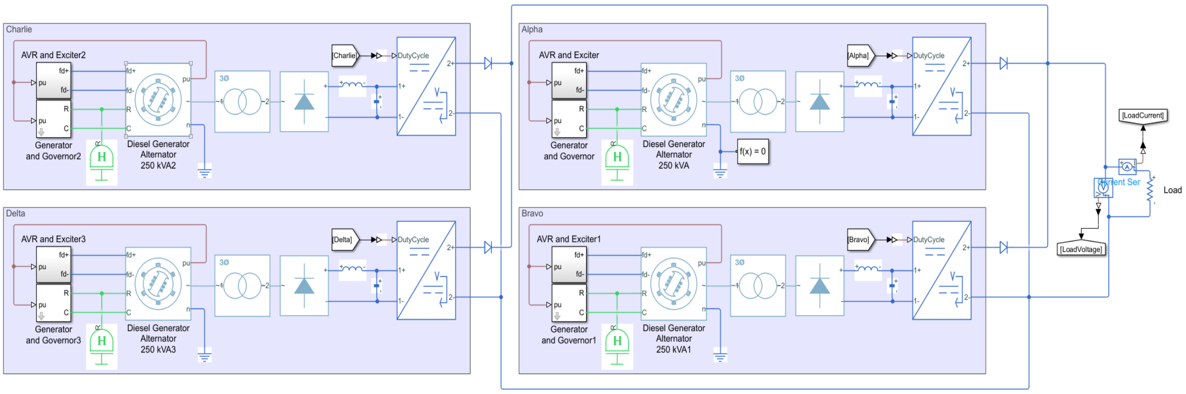


Figure 9. Model of a ‘generator unit’ comprised of four generators, Figure 8, feeding a common DC PCC.

OC Development

The OC approach that seeks to minimize the cost of running each generator while maintaining power quality. Cost in this case does not refer explicitly to a monetary value but rather a mathematical value assigned to the performance of running the generators. The evaluation of cost considers the relevant generator operating criteria. Such criteria are used to develop the cost to obtain a desired behaviour of the system. For example, a generator is most efficient when operated within in a band of operating power. This band of efficiency is where the generator should ideally operate to minimize the required fuel and improve the overall performance of the generator. In this way, the efficiency of the generator can be considered a cost. There are several other metrics that can be evaluated on a generator, but the idea is to reduce the negative scenarios a generator may see and operate a grouping of generators in an ‘optimum’ fashion while adhering to power quality.

Here, the initial OC metrics considered were efficiency, maintenance, and load voltage. The distance away from a target efficiency, and the need for maintenance, are the items being minimized. Utilizing MATLAB/Simulink and an optimal minimization function *fmincon,* a combination of these costs is calculated for possible generator power levels. The *fmincon* function takes the cost equation and searches for a minimum point on the curve through the adjustment of the power level setpoints of the generators. The cost function at the time of this report is as follows:

$$\begin{aligned} cost = \ & efficiencyWeight * 1/sum(generatorEfficiencyCurve(\overline{generators})) \\ & + maintenanceWeight * sum(genMaintenanceLevel * \overline{generators}) \\ & + voltageWeight\left(600 - \sqrt{sum(\overline{generators}) * loadResistance}\right)^2 \end{aligned}$$

Here, $\overline{generators}$ refers to the vector of the four respective generator power commands, $powerTarget$ refers to the power level at which the generator is most efficient, $genMaintenanceLevel$ is a calculation of the maintenance level of the generators, and finally, the $loadResistance$ is the resistance of the load. This equation considers several target metrics and evaluates the cost value. The function, $fmincon$, then iterates and searches for a minimum value of this equation through changing $\overline{generators}$. To maintain power quality, a set of constraints around the voltage were imposed on the system. The optimization function must evaluate values for $\overline{generators}$ such that the system falls within these constraints. The constraints are the load bus’s voltage maximum and minimum. In the evaluation of the optimization effort to date, DC sources are being used to simplify the design of the optimization function. In the future, representative generator models, discussed later, will be used to evaluate deeper power quality metrics such as frequency and more detailed voltage sag. The three weightings $efficiencyWeight$, $maintanenceWeight$, and $voltageWeight$ allow the designer to change the importance of the various cost functions. The $generatorEfficiencyCurve(x)$ function takes the power level of the generator and compares it to a generator curve the user must define before operation. This gives the user the opportunity to select the ideal power levels of the generators more acutely and if desired a curve for each individual generator can be developed and calculated in this function.

To date, the generator model being employed is a general power-controlled source. A power setpoint is given to the generator and it applies in the next time step. This is obviously not realistic for a real-world application, but it is being utilized evaluate the latency and expected performance of the OC. Soon this model will be replaced with the diesel generator model described earlier. To begin, the architecture is loaded with an arbitrary resistive load profile seen in the left side of Figure 10, resulting in the voltage profile seen in the right side of Figure 10. In the beginning, when there is the minimum load, the voltage is not at the target level of 600 V. This is due to the OC trying to enforce generator efficiency. The voltage is still within the power quality window for this experiment, but in the future, this value will be narrowed and tuned to reduce the fluctuation in voltage during low load conditions. The power supplied by each individual generator is seen in the lower left plot of Figure 10, showing how the generators behave when power quality (bus voltage), efficiency, and maintenance are all considered in the optimization. In the simulation, all generators are operational, and all three costs are factored into the control though not all are weighted evenly. Within the plots, there are transients that occur each time the load is varied and there are changes in what each generator supplies, something that is an artifact of the simulation that needs to be addressed in the future, potentially through use of a filter or by smoothing out the transitions using a FLC. The time frame of the spikes is very small, and they have negligible effect on any generator's response. For now, any mitigation effort was omitted to focus on studying how the controller responds to load changes, including the transients. The weight of each cost function can be set arbitrarily or based on a situational requirement. Since a specific generator model with known operational intentions are not being considered here, the weights are only being arbitrarily adjusted as a proof of concept. The lower right plot in Figure 10 plots the relative maintenance value of each respective generator as a function of time. The controller does its best to balance load share according to the changing maintenance level. Each generator is assigned a different rate of maintenance growth per watt of power it supplies according to the matrix [0.5 3.1 3.2 3.01]. While the growth rates are different, the controller is constantly changing the value of the generators to reduce the rate of each generator such that the maintenance grows at similar rates for each generator.

If the efficiency cost is removed from consideration while all generators are still available, the system behaves a little differently when run against the same load profile seen in Figure 10. In this case, the controller only cares about the maintenance and the power quality of the system. The reader should be aware that in most generators, the maintenance is tied to its current power level and efficiency, but for this test, that metric is removed from the maintenance calculation to show how the controller responds without consideration of a target power level. The upper left plot in Figure 11 shows load voltage, the upper right plot of Figure 11 shows how the controller adjusts the power level supplied by each generator to reduce the maintenance cost, seen in the lower plot of Figure 11, of the system. It is readily apparent here that the initial voltage far more consistent at 600 V than it was in the previous case. This is because without the efficiency calculation, the OC is not pushing the generators up to higher power values to approach target efficiency. Notice that the maintenance level for Generator 1 does not grow as sharply as it does for the other three even though it supplies roughly the same power. This demonstrates how costs of each generator are assigned their own unique properties. In this case, Generator 1 is assumed to be a new generator, so its maintenance doesn't grow at the same rate as the other three that are older.

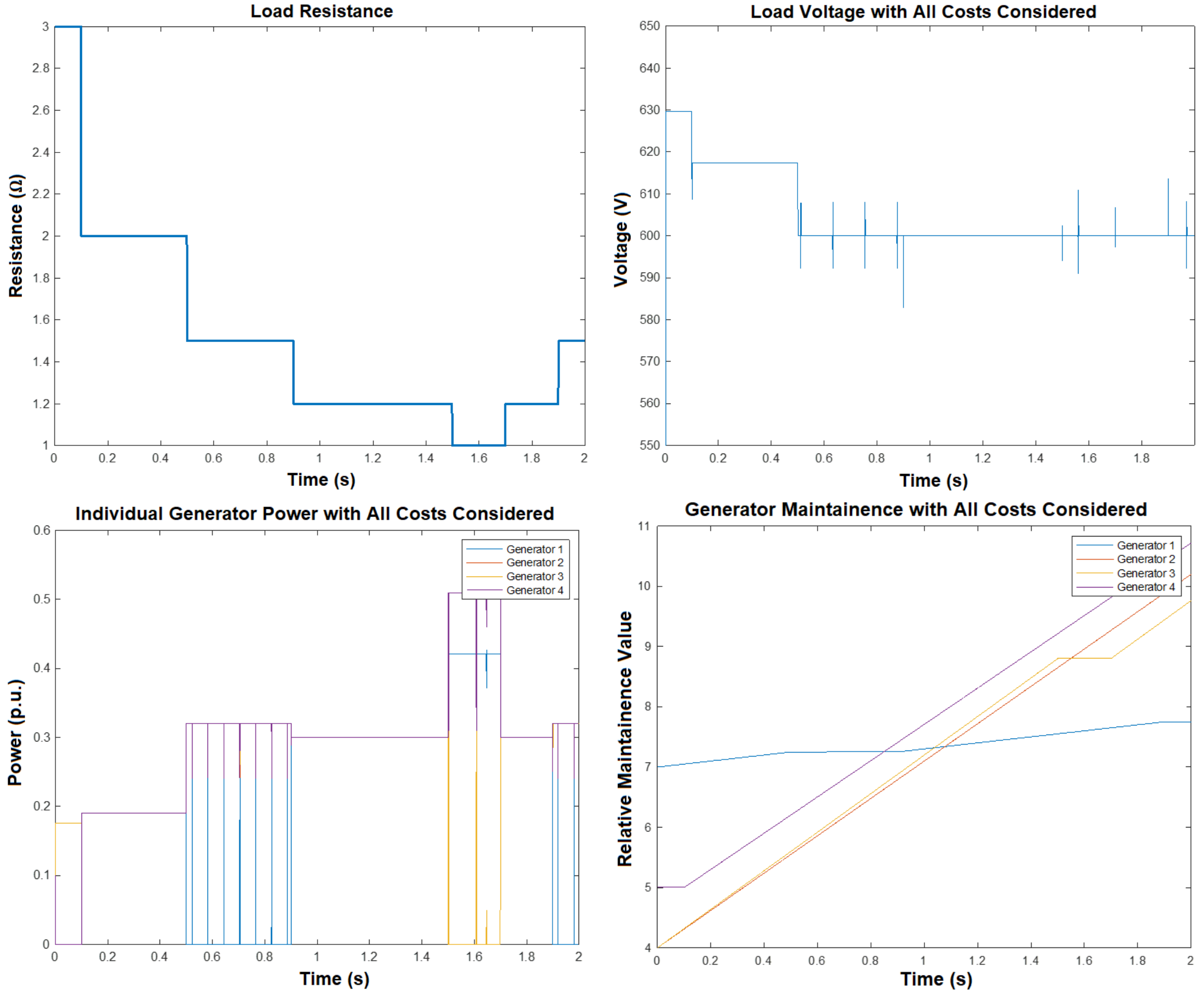


Figure 10. The load profile applied to the DC bus (upper left), the resulting load voltage (upper right), generator load distribution (lower right) and generator maintenance level (lower right) when efficiency, maintenance, and power quality cost functions are all considered.

In the final scenario, the loss of a generator is considered when the same load profile in Figure 10 is executed. When a generator goes down, its maintenance is made to be a very high value, telling the controller that it cannot be used. This could occur because of a fault or due to routine maintenance where the generator is taken off the bus. How the controller responds to a loss of generator situation when all three costs are considered is evaluated here, seen in Figure 12. Since efficiency is again being considered, the voltage in the upper left plot of Figure 12, does not hold perfectly steady at 600 V but it is always maintained within the allowable power quality limits. Each generator's power distribution is plotted in the upper right plot of Figure 12. The power each supplies is held pretty even until Generator 4 falls offline 0.85 s into the simulation. This forces the other generators to be used more heavily and makes it harder to reduce one generator in favour of another for the purpose of hitting target efficiency. The inability to lower some generator(s) power causes the maintenance costs to grow sharply, seen in the lower plot of Figure 12. The slopes of each respective maintenance growth are less parallel than in previous scenarios which points to a more balanced generator usage. Generator 1's maintenance again grows more slowly since it is a newer generator.

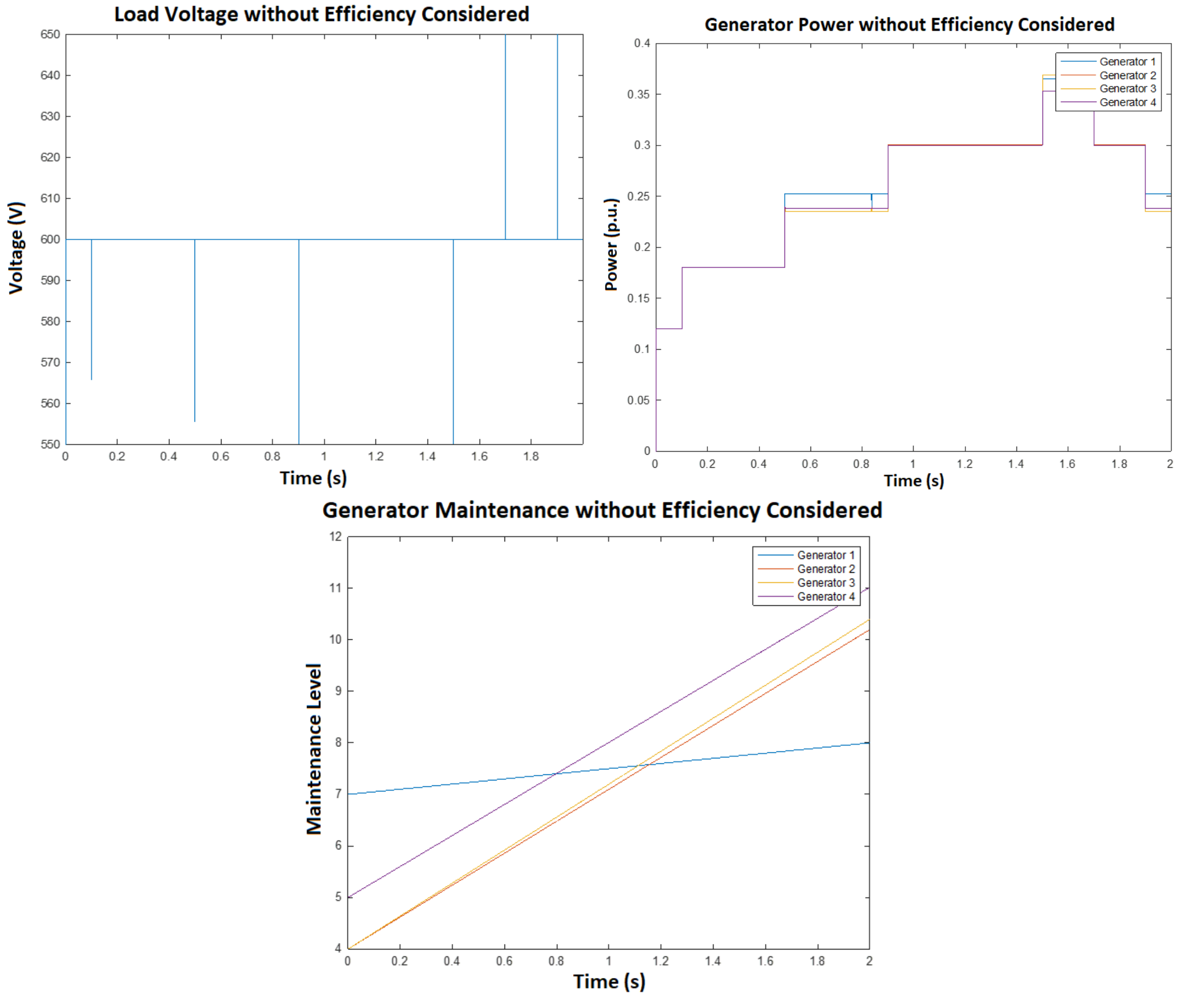


Figure 11. Load voltage (upper left), generator load distribution (upper right), and generator maintenance levels (below) when maintenance and power quality are considered but efficiency is not.

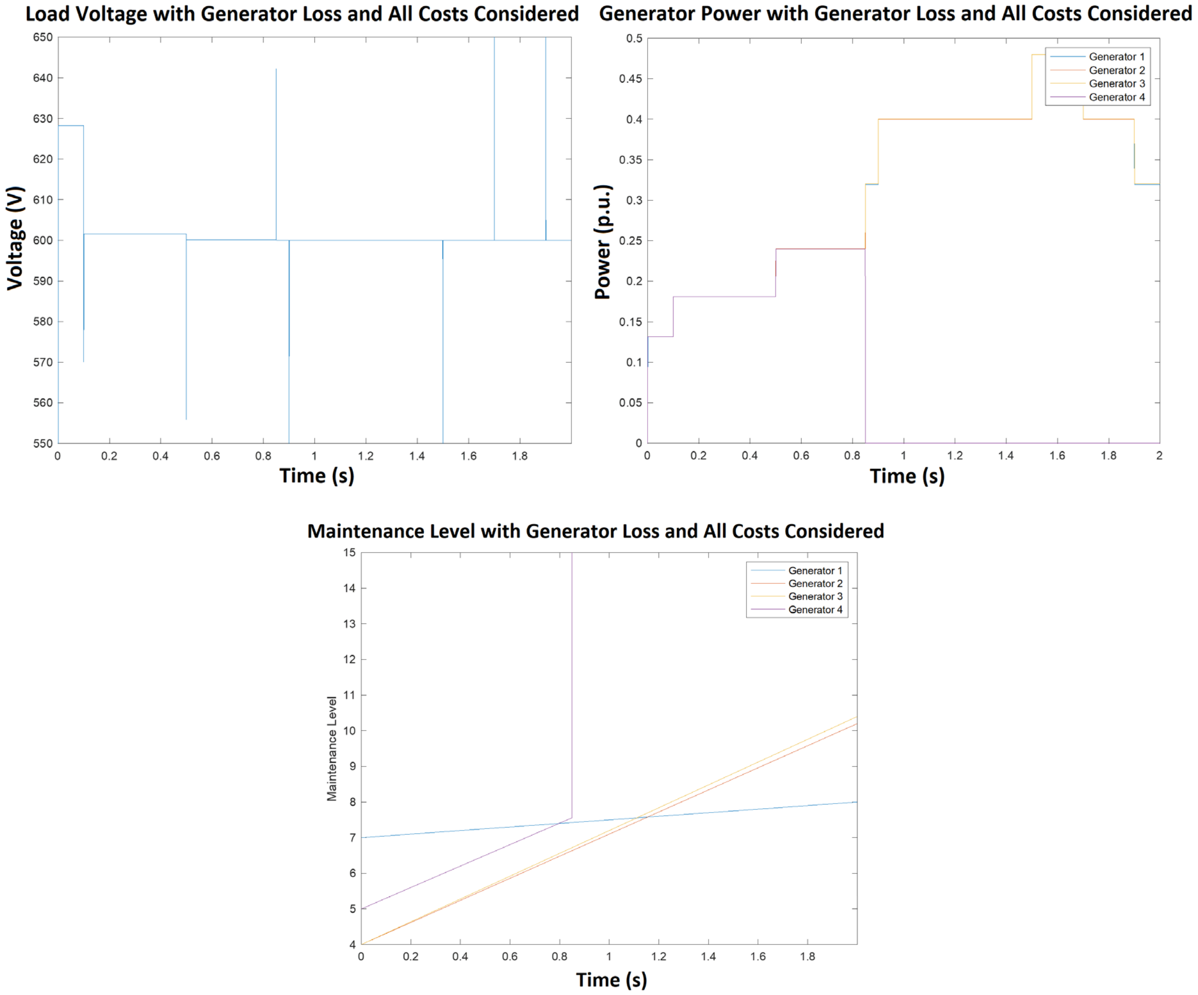


Figure 12. Load voltage (upper left), generator load distribution (upper right), and generator maintenance levels (below) when a generator drops offline, and all costs are considered.

FLC Development

To date, the FLC is being used to assign a grade to a generator based on the different metrics that are important to the generator operator. For this grading FLC being worked on here, the metrics are the generator's maintenance, efficiency, and power quality (voltage deviation), shown at a high level in Figure 13.

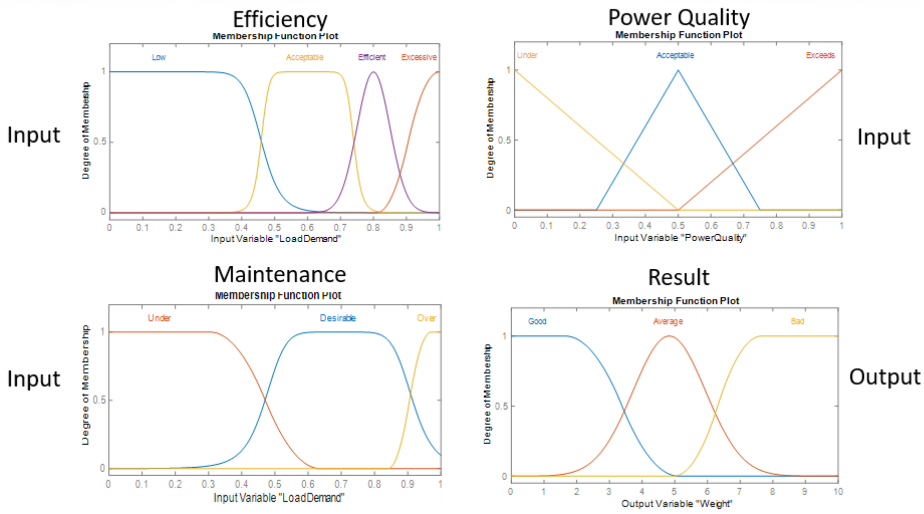


Figure 13. Generator grading FLC membership functions.

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Each of the metrics can be weighed, or prioritized, to change their impact on the generator(s) set points. Each metric being tracked has overlapping membership functions associated with them that affect the output grading based on the input. The main factor that affects them is the p.u. loading the generator is experiencing, but in the future different inputs can be considered. Within each metric is a group of membership functions and the output for each group is a number between 1 and 2 which is used to create a final output/grade. The output of the whole FLC, when considering all the different metrics and after the defuzzification process, is a number between 1 and 10, where 1 is ‘Good’ and 10 is ‘Bad.’

The ‘Maintenance’ group of membership functions is shown in Figure 14 where the input is the p.u. loading of the generator and it has three membership functions. The ‘under’ membership function places the output in the ‘bad’ output range, the ‘over’ results in the ‘average’ output range, and the ‘desirable’ membership function results in the ‘good’ output range. This metric is meant to be a measure of how much the loading of the generator is affecting how soon the generator needs to be serviced. Loading the generator too lightly or too heavily can cause the generator to need to be serviced sooner, so this group of membership functions can be used to prevent those two cases.

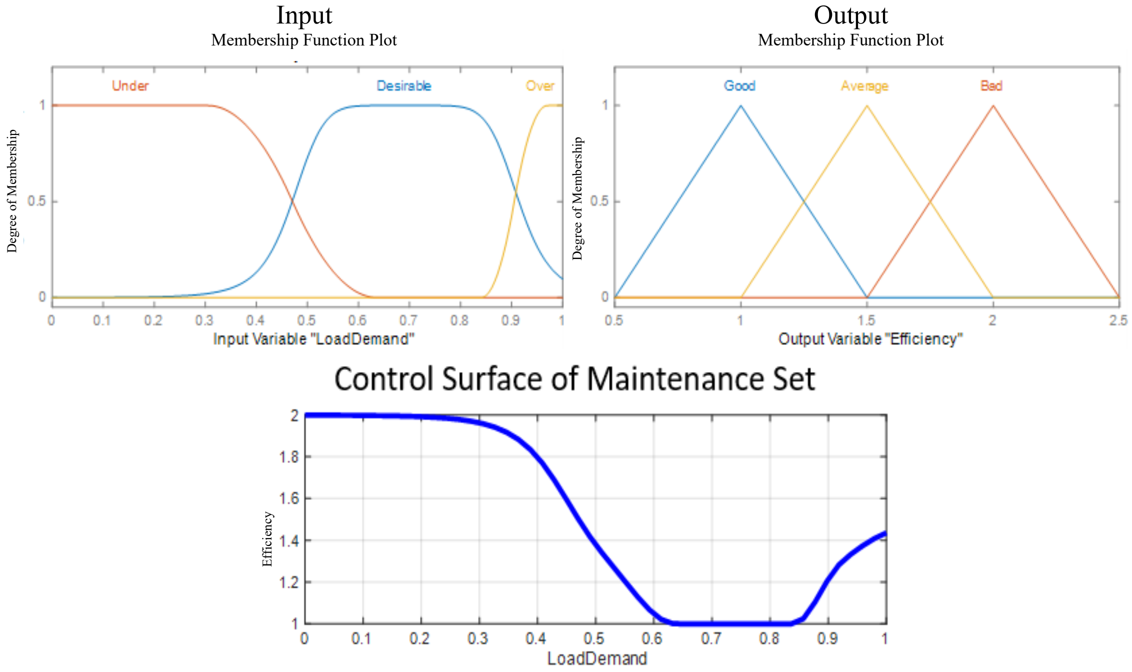

Figure 14. Maintenance membership function.

The ‘Efficiency’ group of membership functions in Figure 15 where the generator’s p.u. loading is again used as the input, and it has four membership functions. The ‘low’ input curve is associated with the ‘bad’ output range. The ‘Acceptable’ and ‘Excessive’ input curves result in the ‘Average’ output range, and the ‘Efficient’ input curve results in the ‘Good’ output range. This metric is meant to map the current loading of the generator to the quantity of resources required to run the generator. These membership functions can be changed to fit a generators specific efficiency curve. As seen in the control curve, the output is lowest/best value when the generator runs at 0.8 p.u. loading (picked arbitrarily) while it outputs the highest value when the p.u. loading goes below 0.4 p.u. operating power.

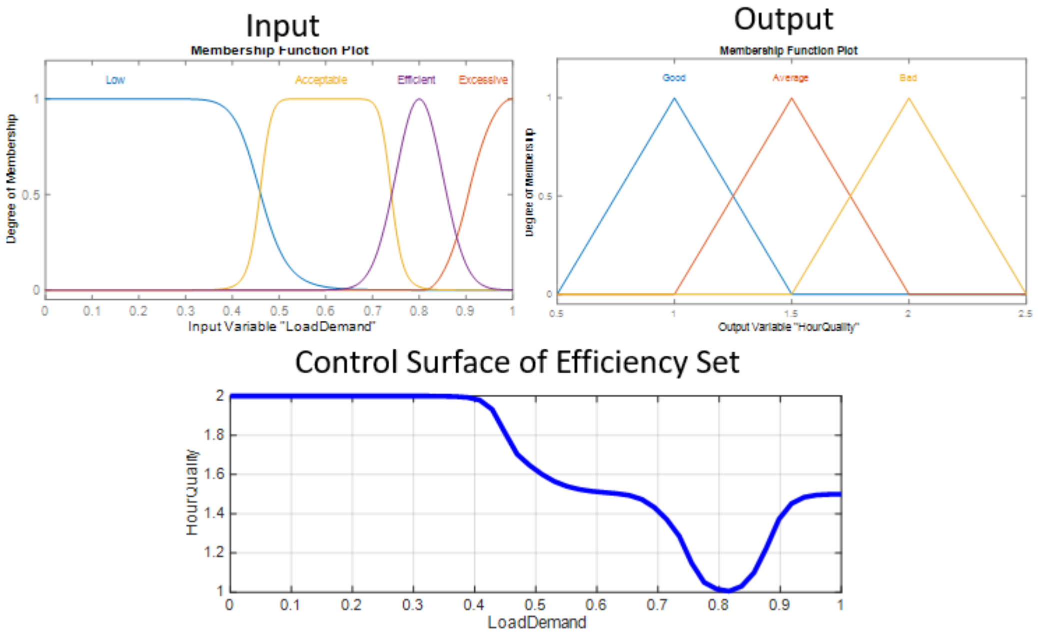

Figure 15. Efficiency group of membership functions.

The ‘Power Quality’ group of membership functions are shown in Figure 16 where the input is the p.u. rate of change of the generator loading and it uses three membership functions. The ‘Under’ and ‘Over’ input curves result in the ‘Bad’ output range while the ‘Acceptable’ input curve results in the ‘Good’ output range. It should be noted that the overlap of the ‘Under’ and ‘Over’ curves with the ‘Acceptable’ input curve is meant to help make a distinction between transient loading and ramped loading. One of the worst things that could be done to a generator’s power quality is to give it a large transient load, which is why the distinction between transient loading and ramped loading is present in this group of membership functions.

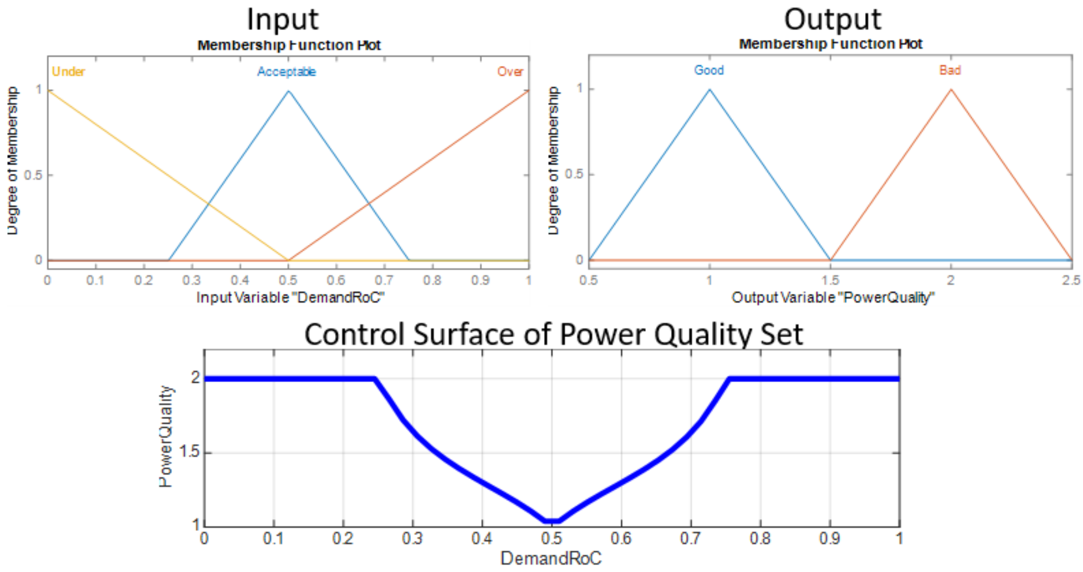

Figure 16. Power quality group of membership functions.

A very simple simulation using two simulated generators, presented earlier in Figure 8, is shown in Figure 17. The purpose of this simulation is to demonstrate how generator priority and current limiting works as well as how they work together to balance the generators output power. These three factors could be controlled by the FLC or used by an operator to command how the generators behave. Figure 17 plots the current supplied by the two parallel generators while maintaining an arbitrary bus voltage of 300 V with the current limit on each generator set to not exceed 300 A. The load starts by demanding 200 A. After 3 seconds, the load starts to ramp up to 500 A over the next 9 seconds. Initially the generators share 100 A of current each but Generator 1 is given priority to pick up load slowly, so it starts ramping up, taking over the full 200 A just before the load starts to increase. As the load ramps, Generator 1 continues to pick it up until roughly 6 seconds into the simulation when a generator balancing command is given causing the two generators to start sharing the load equally. At roughly 9.5 seconds, the balance command is disabled, and Generator 1 starts to take over more load again until it reaches its 300 A current limit. Once this happens, Generator 2 picks up the rest of the ramped load while Generator 1 continues to supply its maximum of 300 A.

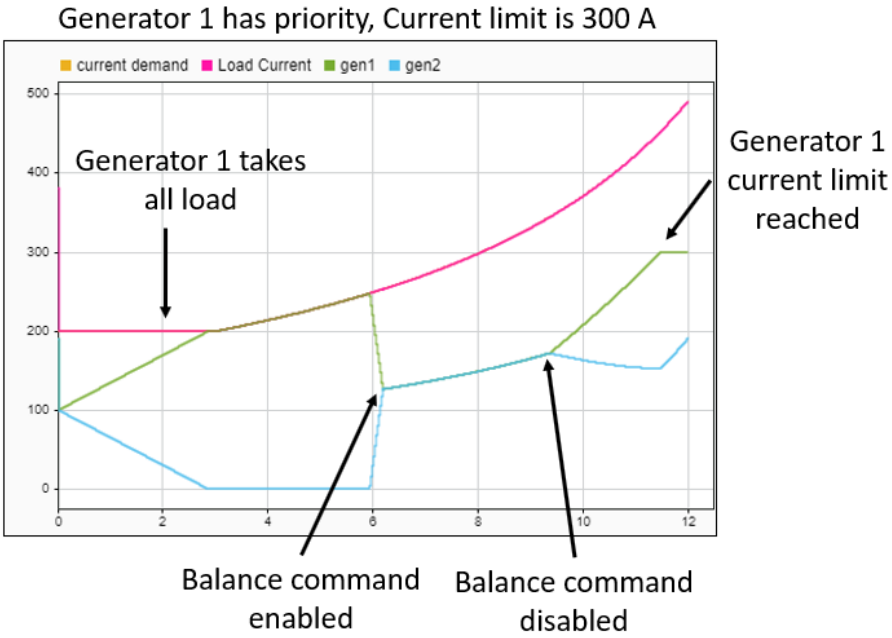

Figure 17. Test with two generators to show gen priority, current limit, and balancing.

4. Conclusions

This report has described an approach to replacing larger generator sets in shipboard power systems with multiple smaller generators that can supply the same total load. It has been described that this approach may afford many benefits when they are actively controlled using power electronics. It is proposed that the power quality, efficiency, and MTBF of each generator can be optimized to achieve the best results and highest level of reliability. Optimal control (OC) and fuzzy logic control (FLC) strategies are being explored to regulate the power supplied by each generator in real time. To date, frameworks using each type of control strategy have been developed and both are now in the stage of being flushed out. It would be ambitious to say a working model is close to completion as much work is still needed. Development of the FLC is ongoing and will integrate the OC solutions presented soon. Once the model has been verified and validated, many different tests will be performed to verify and validate its operation under unique load profiles.

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