Informing the power system performance envelope for pulse load operation

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Synopsis

Future warship power systems may be subject to pulsed loads manifesting through emergent combat systems such as directed energy weapons, associated sensors and electronic warfare equipment. The integration of combat system loads with the ship's power system means that performance becomes intrinsically linked to combat effectiveness. Hence, understanding the capability of the power system to service such loads is vital in ensuring the operator's ability to fight the ship.

This paper describes the challenge of pulse load integration from the perspective of the power system design authority. Modelling and simulation has been employed to study the electrical response of a representative power system when subject to a range pulse load characteristics. Subsequently, the effects of pulse loading are reviewed in terms of impact upon the prime mover. It is concluded that whilst electrical supply performance can be maintained within allowable power quality limits as defined by STANAG 1008, the mechanical effects can be to the detriment of engine life, highlighting key recommendations to understand both electrical and mechanical performance envelope in design for integration.

Keywords: Electrical power system; Power quality; Diesel generator performance; Combat system integration

1 Introduction

Over the past decade research into the integration of pulse loads with warship electric power systems has made the fielding of Directed Energy Weapons (DEW)s realisable in the near term. An example is the United States Navy's intention to field a laser weapon at sea in the 2020 time frame (Freedberg, 2018) (Scott, 2018).

To enable effective integration, the power system design authority must have a complete understanding of the power system performance envelope, from both an electrical and mechanical perspective, when subject to pulse type loading. Understanding around the impact of pulse loads on power system performance from an electrical perspective has increased in recent years (Daffey & Hodge, 2004) (Lewis, 2006) (Tsekouras, Kanellos, Prousalidis, & Hatzilau, 2010), with energy storage referenced as an enabling technology (Gonsoulin, Vu, & Diaz, 2017) (Khan & Faruque, 2017).

However, how the possible range of pulse load characteristics possible effect the mechanical system, and the associated translation from electrical performance is less well understood. Smolleck, et al., (1991), Baldwin (2004), Dehkordi, et al. (2007) and Boehmer & Temkin (2018) all conclude that pulse type loading can place increased stress on the mechanical components of the generator set, particularly the prime mover. In terms of power system performance, this may manifest as a reduction in Mean Time Between Overhaul (MTBO). This is of particular importance when considering ship affordability, as reduced MTBO may erode the Through Life Cost (TLC) reductions realised through the low incremental cost per shot (Dunn, 2005) of DEWs.

Hence, a research need exists to understand both electrical and mechanical power system performance elements under pulse type loading, such that the power system design authority can realise a more complete understanding of the power system performance envelope when designing for integration.

Authors' Biographies

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2 Electrical power system characteristics and constraints

2.1 Naval electrical power systems standardisation

Shipboard electrical power systems are designed to maintain Quality of Power Supply (QPS) to connected electrical consumers to ensure compatibility at the point of interface. Standards are employed by the power system design authority to define the conditions which connected electrical consumers shall be designed to tolerate. The implication from the power system perspective is that operation outside of the agreed bounds may lead to loss or malfunction of any number of connected loads.

For warships of North Atlantic Treaty Organisation (NATO) navies, NATO Standardisation Agency Standardisation Agreement (STANAG) 1008 is recognised as the baseline for characteristics of shipboard low voltage (LV) electrical power systems. The parameters considered during this investigation are provided in Table 1.

Table 1: Characteristics of standard 60 Hz supplies, in accordance with STANAG 1008

Frequency parameter	Value
Tolerance	± 3%
Modulation	0.5%
Transient tolerance	± 4%
Transient recovery time	2 s
Maximum departure from nominal frequency due to combined effects	± 5.5%

STANAG 1008 explicitly discusses pulsed loads, and stipulates limits to constrain their application. The standard specifies that pulse load real power should be no greater than 25% of full rated apparent supply power at the occurrence of the pulse. If deviation from this constraint is required, consultation with the client and their power system design authority is recommended by STANAG 1008, to determine suitable corrective action.

This sets the context within which the power system design authority may act to manage the integration of pulse loads; however no equivalent standards govern the approach to electrical power system design in this context. Hence, for the power system design authority to be informed in this role, there is an impetus to study the system response.

2.2 Context for investigation

This study is framed from the perspective of the power system design authority and therefore looks to understand the power system performance envelope when pulse load characteristics exceed the real power limits prescribed by STANAG 1008.

Although this study adopts a system voltage of 690 V rather than 440 V, the characteristics defined in Table 1 will be adopted as the benchmark for performance assessment. In relation to this, it is important to acknowledge that the complete power system need not be constrained to maintain QPS in accordance with STANAG 1008 or equivalent. Platform designers are free to specify differing voltages and power quality, for example, serving electric propulsion systems, provided the ship service supply made available to LV consumers is maintained to an agreed QPS standard. In the context of integrating pulse loads, this does provide the option to configure the power system such that the pulse load and its generation source are isolated from the principal ship service supply system. This will be discussed where informed by the investigation results in section 4.

3 Investigation of power system capability under pulse loading

The objective of this study has been to determine the impact of pulse loads on the envelope of acceptable power system performance. Acceptable performance is considered both in terms of the capability of a warship electrical power system to maintain an acceptable standard of QPS and in terms of the resultant operating capability of the prime mover generator set. Modelling and time-based simulation is selected as the primary method for investigation, as this offers the freedom to quickly examine a number of test cases imparted upon a reference system configuration without incurring the expense of experimental testing.

By modelling a representative hybrid electric power system, defined in section 3.1, time-based simulation has been used to explore an array of pulse load configurations against relative electrical system base loads. The purpose of the investigation is twofold;

1. To examine the impact of pulse load characteristics on the QPS. This will be achieved by recording and analysing the resulting power system electrical response.

2. To enable comment on the impact of pulse load characteristics on the prime mover generator set itself. This will be achieved by reviewing the effects of pulse loading on a typical marine diesel engine coupled to an alternator.

3.1 Power system configuration

A typical warship hybrid electric power and propulsion system has been selected based on a Combined Diesel Electric Or Gas (CODLOG) configuration. An installed generation capacity of 12 MW is provided by four 3 MW diesel generators, arranged over two 690 V main switchboards, interconnected via a bus coupler. The loads to each switchboard comprise propulsion and service loads, with the addition of the pulse load on one bus only.

For the purpose of this investigation, the following assumptions were applied to form a representative worst-case scenario, cognisant of likely operational constraints in place to ensure maximum survivability in a high-threat state:

1. The electrical power system is operating in split bus configuration.
2. During pulse load application the ship will be configured to operate under mechanical propulsion, provided for by gas turbine direct-drive.
3. Only one diesel generator is connected to the bus.

The resultant system of interest defined for this study is highlighted within in Figure 1.

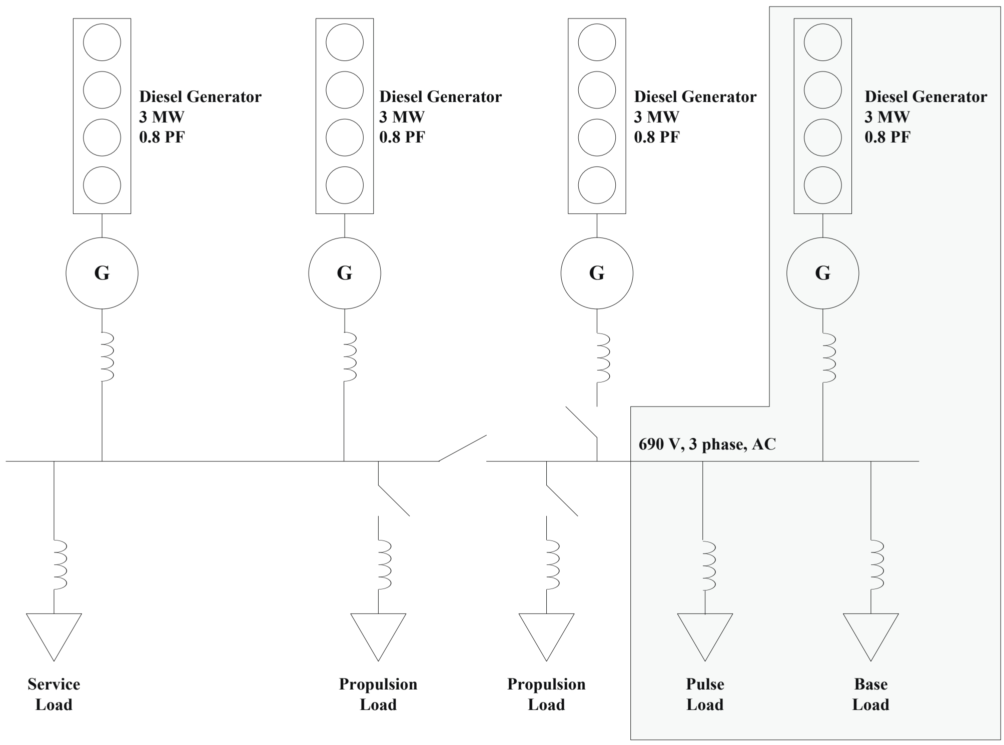

Figure 1: Power system defined for investigation, to consider a CODLOG hybrid electric configuration operating with a split bus and a single diesel generator connected to supply the pulse and base loads

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3.2 System modelling

The model to represent the defined power system has been developed in MATLAB® Simulink®. Depicted in Figure 2, the model approximates a diesel engine and generator, and has been created based upon a previously established model (Wilson, et al., 2017) . Its principal components are further described below.

Given the objectives to study power system performance under pulsed loading, elements which dominate the electrical response are explicitly studied. In doing so, it should be noted that mechanical behaviour of the engine is represented in a much simplified manner. Alternate modelling approaches which better represent the engine performance are considered by this paper as part of verification and discussion, in sections 3.2.3 and 4.2, respectively.

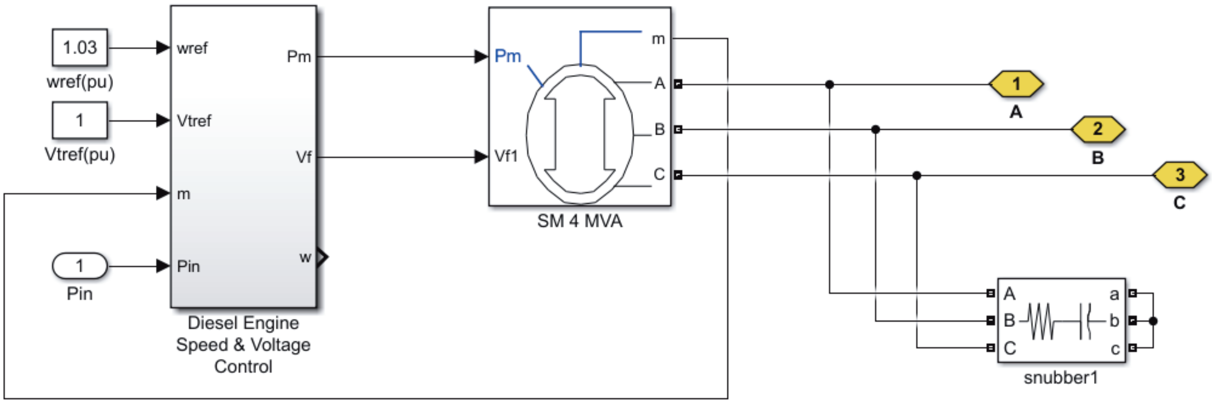

Figure 2: Overview of representative diesel engine and generator model in Simulink®

3.2.1 Generator model

The generator model employs a standard Simulink® synchronous machine block. Generator parameters were selected based upon a standard marine diesel generator of 3 MW nominal power, 1800 rpm rated speed and 185 kgm² lumped inertia. The complete parameter set is recorded within Appendix A. Calculation of the stated inertia coefficient *H* is in accordance with equation 1:

$$H = (\frac{1}{2} J \omega_o^2)/P \quad (1)$$

Where ω_0 = nominal angular frequency (rad/s), P = rated power of the synchronous machine (W),
J = moment of inertia for rotor (kgm²)

The lumped inertia is utilised for this calculation to satisfy assumptions defined within the diesel engine and governor model, presented below.

3.2.2 Engine speed and voltage control system

The "Diesel Engine Speed & Voltage Control" block forms a representation of the diesel engine control system, specifically its governor, excitation system and Automatic Voltage Regulator (AVR), arranged as shown in Figure 3. The governor, excitation system and AVR are implemented initially with use of Simulink® blocks, established by (Yeager & Willis, 1993) and IEEE Recommended Practice (IEEE, 1992).

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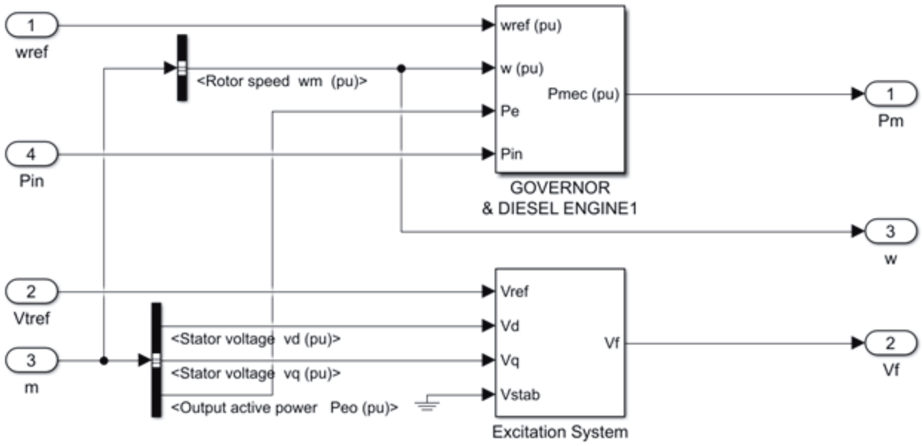


Figure 3: Diesel engine speed and voltage control model in Simulink®, representing the diesel engine governor, excitation system and automatic voltage regulator

The governor control system was subject to study and tuning. The model itself is formed by a series of transfer functions, characterising the response of the controller and the actuator, with an additional time delay associated with the engine response. The model also includes torque limits, representing the bounds of the physical system. For this study, the engine governor is in droop control with a 3% speed droop characteristic, representative of a typical engine control configuration. Definition of the transfer functions and associated parameters are recorded within Appendix B.

To account for no-load friction losses, the curve fitting tool in MATLAB® was used to represent friction versus speed as a polynomial function, based upon a series of data points collected from reference marine diesel engine characteristics. With friction obtained as a function of speed, a Simulink® block was created to convert engine speed into rotor torque, in the no-load condition. The modified engine and governor model is shown in Figure 4.

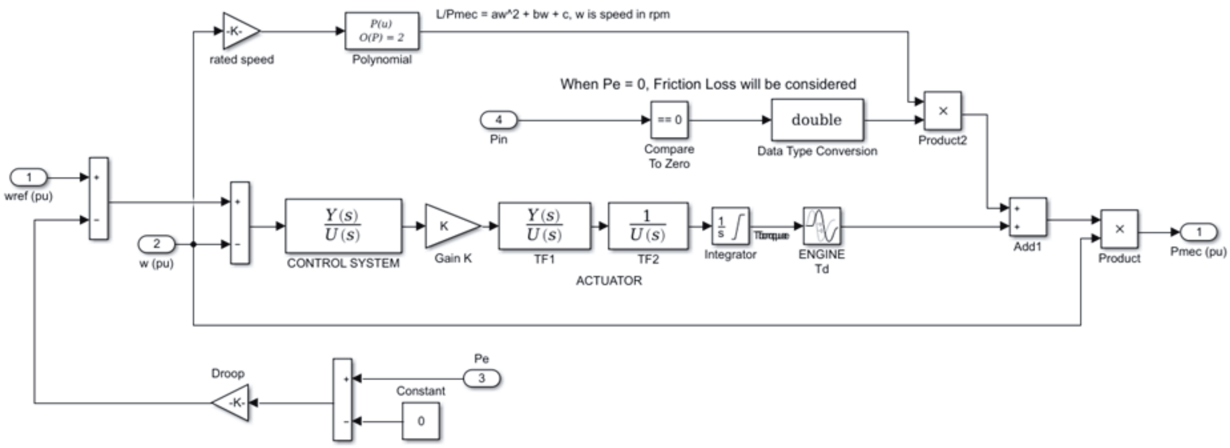


Figure 4: Modified engine and governor model in Simulink® showing component parts of the governor control model and additions made to account for no-load friction

3.2.3 Model verification

Due to the significant influence on the power system response, the diesel engine governor and AVR models have been verified by test to ensure behaviour is representative of a typical real world marine diesel engine, which they are intended to represent.

The governor model was initially verified against a detailed GT-SUITE® engine reference model, which itself has been validated against a real world diesel engine response provided by Rolls-Royce Power Systems. The test was adopted iteratively to assess performance of the proposed model, such that the control system parameters could be adjusted to minimise error relative to the reference model. Test descriptors and measured results from the finalised model are provided in Appendix C.

Residual discrepancies between the models are attributed to the simplified modelling approach employed in the Simulink® environment, as the reference model includes significantly more detail with regard to performance of engine mechanical and control subsystems. Worst-case errors less than 2% have been deemed tolerable within the context of this study. The implications of the modelling approach are discussed in section 4.

Further to model comparison, additional verification procedures have been derived from performance criteria specified within Lloyd's Register Rules and Regulations for the Classification of Naval Ships (LRNS) (Lloyd's Register, 2018). The test sequence for the governor applies the cases defined in Volume 2, Part 2, Chapter 1, 9.3.1, whilst the AVR test cases are in accordance with Volume 2, Part 9, Chapter 2, 6.4.4.

Test descriptors, performance criteria and measured results are provided in Appendix C. Both the AVR control and governor frequency control response are demonstrated to meet the requirements stated within LRNS, thus the simulation model is considered verified for the purpose of this investigation.

3.2.4 Pulse load and base load

The combined profiles of pulse load and base load are modelled as a direct power demand on the diesel generator. For any given test scenario, the base load remains constant, with the pulse load introduced as an additional square load step, repeated with a duty cycle of uniform duration. To form the basis for performance comparison, parameters have been examined over a range of values, as defined by Table 2. The range of characteristics presented in Table 2 are considered representative of a candidate DEW (Whitelegg, Pawling, & Bucknall, 2014)

Table 2 Load characteristics examined

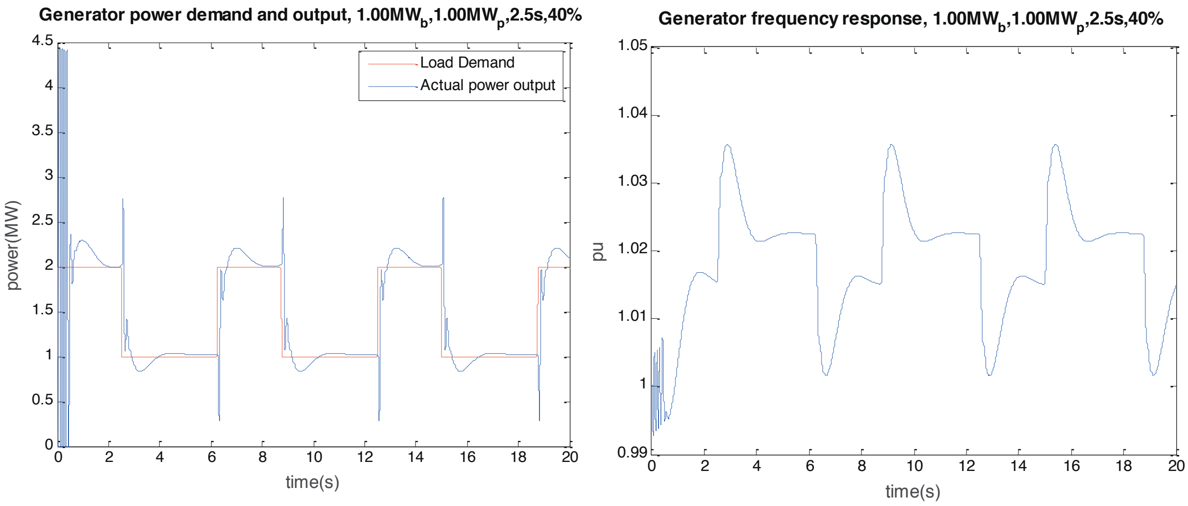
Variable	Examined values
Pulse load magnitude (MW)	0.25, 1, 1.5, 1.75, 2
Active pulse duration (s)	2.5
Duty cycle	40%
Base load (MW)	0.25, 0.5, 0.75, 1

The entirety of available combinations formed the complete test case set, with simulations conducted to verify all cases and to examine trends across parameter ranges. The results are presented in section 3.3.

3.3 Simulation results

3.3.1 Diesel generator response

For each simulation, the actual power output of the generator is observed relative to the load demand profile of the summed pulse and base loads, with corresponding frequency variations recorded. Figure 5(a) shows the response of the diesel generator, for the case where a pulse of 1 MW magnitude, 2.5 s active pulse duration and 40% duty cycle is applied against a base load of 1 MW. Peaks are observed at the start and end of active pulse loading. Due to the cyclic demand of the pulse load, the frequency of the generator is affected as shown in Figure 5(b).



(a) (b)

Figure 5: Simulated results where a pulse of 1 MW magnitude, 2.5 s active pulse duration and 40% duty cycle is applied against a base load of 1 MW, showing (a) generator power demand and response, and (b) generator frequency response

Initialisation of the model within the first second of the simulation is disregarded, with subsequent cycles used to interpret the generator behaviour. At the point of a pulse on step change, for example 6.25 s and 12.5 s, the frequency drops as rotational energy is extracted to meet the additional power demand. Initially, this response will be dominated by the lumped inertia characteristic, until the governor control acts to increase energy in, by increasing the fuel flow to return the engine speed to its reference value for the load condition.

During each pulse, a minimum frequency of 1.0016 pu is observed, which equates to 60.1 Hz. Given the droop characteristic, this marks a 1.34% transient frequency variation against a 1.015 pu reference for the 2 MW combined load. Frequency has not attained steady-state by the end of the on pulse.

The pulse off point then initiates the sudden decrease of load, causing the engine speed to increase and a corresponding over-frequency due to the short term excess of energy available within the system. Again, the control system acts to return engine speed to its reference. Maximum frequency is measured as 1.0357 pu, equating to 62.1 Hz. This then marks a 1.32% transient frequency variation against a 1.0225 pu reference for the 1 MW base load. In this phase of the load cycle, recovery to steady-state is achieved in approximately 3 seconds.

3.3.2 Response given variation in load characteristics

Looking beyond the isolated case above, it has been the intention to consider power system performance given changing definition of both pulse and base load characteristics. For each test case, the overall profile of the frequency response is broadly consistent with that observed in Figure 5(b), but with varying magnitudes of frequency excursion observed; the trends are shown in Figure 6.

With increasing base load the maximum measured frequency shows a gradual decrease, whilst increasing pulse load increases the maximum frequency deviation significantly over the examined range. The worst case frequency deviation is observed given a 0.25 MW base load subject to a 2 MW pulse; maximum frequency for this case is measured as 5.42% above nominal, which is equal to 63.3 Hz. As previously described, this deviation represents both the droop offset and the transient response to the pulse load; the transient variation being 2.61% in this worst-case scenario.

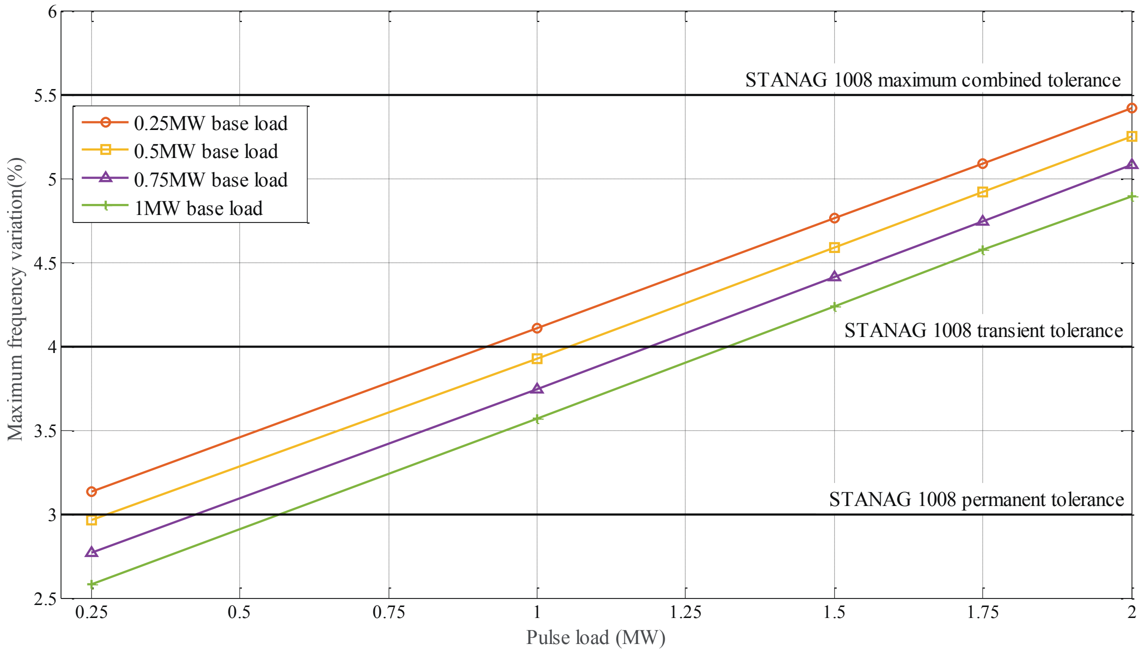


Figure 6: Maximum frequency variation given increasing pulse load and varied base load; maintaining 2.5 s active pulse duration and 40% duty cycle

4 Discussion

4.1 Performance against STANAG 1008

Revisiting the frequency characteristics presented in section 2.1 provides the basis to interpret the study results and then deduce the performance envelope. Modulation effects are the focus of STANAG 1008 when concerned with mitigating the effects of pulsed loads; however, the pulse load size constraints placed to achieve this are identified as restrictive. For the diesel generator nominal power considered in this study, the limits would recommend pulse loads no greater than 937.5 kW. From the test cases satisfying this condition (where pulse load equals 0.25 MW), it was confirmed that frequency modulation was maintained below the required 0.5%. However, this was not achieved for larger pulse loads and so non-compliance with frequency modulation limits is acknowledged for the majority of cases. It therefore becomes necessary to look at the transient tolerances as a subsequent point of reference.

Transient tolerances account for sudden but temporary power excursions above tolerance limits, attributed to occasional events within the bounds of normal operation, for example large motor starts. The base tolerance limits provide the allowance for variations forming part of system design, with governor droop factored here. To assess the overall frequency variation, as has been measured for the test cases, the maximum departure due to combined effects is therefore taken as a point of reference.

Figure 6 illustrates that frequency variation can be maintained below the 5.5% maximum departure expressed within STANAG 1008 for all studied cases. The scenarios with lower base load are afforded less margin for the transient element of frequency response given the higher reference frequency under droop; nonetheless, the transients introduced by the increasing pulse loads do not exceed allowable limits.

Referring back to Figure 5(b) it is shown that although achieving steady-state can take up to 3 seconds, frequency variation returns to within the 3% tolerance threshold in approximately 0.7 seconds. For the case of worst overall frequency excursion (0.25 MW base load, 2 MW pulse load), the frequency returns to tolerance within 1.2 s. It is therefore concluded that if pulse loads may be treated as repeated transients on a power system, the electrical performance at least, can be controlled within limits of acceptable QPS as defined by STANAG 1008.

4.2 Interpretations for a physical system

Whilst the demonstrated frequency response is tolerable from a QPS perspective, the impact of sizeable cyclic loading on the physical system components presents cause for concern. It is now pertinent to acknowledge the limitations of the simplified modelling approach. Whilst justified in the study of electrical response, the resultant mechanical behaviour and effects are not fully represented.

As noted in the verification exercise, there are physical limitations beyond those factored which limit the engine's ability to respond to significant step changes in load. In practice, ramp rates for load increase over a number of seconds are necessary to allow for the necessary intake of combustion air, which cannot be realised instantaneously. Relatively high power cyclic loading has been shown to subject engine components to increased thermal stresses. Where design assumes such significant load steps to be undertaken occasionally as opposed to repeatedly, pulsed loading may lead to excessive thermal cycling, reducing component life and manifesting as a reduced MTBO, with consequential engine TLC implications.

Clearly, understanding of this behaviour plays an important part in the design decision process on how best to integrate pulse loads within a warship power system. System design which either tolerates the transient behaviour described by this study, or adopts the option to isolate the pulse load and its generation source as acknowledged in section 2.2, can offer appropriate QPS performance. However, both options may result in mechanical stresses to the detriment of engine MTBO. Cognisant of the limitations imposed by the simplified modelling approach adopted in this study, it is recommended that further work be undertaken to fully understand the impact of pulse type loading on the mechanical components of the power system.

5 Conclusions

This paper has described the challenge of pulse load integration from the perspective of the power system design authority. Modelling and time-based simulation has been employed to study the frequency response of a representative power system when subject to a range of pulse load characteristics, representative of candidate DEWs. Subject to the limitations of the model, it is concluded that the electrical performance can be maintained within allowable QPS limits as defined by STANAG 1008.

In identifying a tolerable position with regard to electrical performance, it is concluded that the burden placed on the mechanical system should also be considered. Furthermore, it is proposed that the conclusions drawn from this research are not unique to the pulse load problem posed within the paper. Acknowledging parallels across other transient load scenarios emerging from intentional operational demands or unintended failure consequences, both of which may yield step changes in load, further emphasise the case for realising a more complete understanding of the power system performance envelope.

The key reflection from this study has been to recognise and highlight the interdisciplinary nature of the integration problem and resulting modelling approach required; looking beyond electrical power quality, to a more holistic, system-level appreciation when designing for integration.

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Nomenclature

H	Inertia coefficient
Hz	Hertz
J	Moment of inertia
kgm^3	kilograms metres cubed
kW	kilo watts
MVA	Mega volt-amps
MW	Mega watts
P	Power
pu	Per unit
rad/s	Radians per second
rpm	Revolutions per minute
s	seconds
W	Watts
w	Speed
ω	Angular frequency
V	Volts, voltage

Glossary of terms

AC	Alternating Current
AVR	Automatic Voltage Regulator
CODLOG	Combined Diesel Electric Or Gas
DEW	Directed Energy Weapon
LRNS	Lloyd's Register Rules and Regulations for the Classification of Naval Ships
LV	Low Voltage
MTBO	Mean Time Between Overhaul
NATO	North Atlantic Treaty Organisation
NTU	Nanyang Technological University
PF	Power Factor
QPS	Quality of Power Supply
STANAG	Standardisation Agreement
TLC	Through Life Cost

Appendix A: Generator parameters employed for synchronous machine model

Table 3: Synchronous machine parameters

Parameter	Value
Nominal power	4 MVA
Line-to-line voltage	690 V
Frequency	60 Hz
Inertia coefficient	1.1 s
Friction factor	0.005 pu
Pole pairs	2

Parameter	Value
Synchronous reactance (Xd)	187%
Transient reactance (X'd)	21.9%
Sub-transient reactance (X"d)	11.6%
Synchronous reactance (Xq)	105%
Sub-transient reactance (X"q)	12.1%
Leakage reactance (Xl)	10%

Parameter	Value
Time constant (d-axis)	Short-circuit
Time constant (q-axis)	Short-circuit
Transient time constant (T'd)	0.35 s
Sub-transient time constant (T"d)	0.029 s
Sub-transient time constant (T"q)	0.011 s
Stator resistance	0.2581%

Appendix B: Governor model transfer functions and parameters

The controller transfer function is described by equation 1.

$$H_c = K \cdot \frac{(1 + T_3 s)}{(1 + T_1 s + T_1 T_2 s^2)} \tag{2}$$

The actuator transfer function is described by equation 2.

$$H_a = \frac{(1 + T_4 s)}{s \cdot (1 + T_5 s)(1 + T_6 s)} \tag{3}$$

Table 4: Governor model parameters

Parameter		Value
Regulator gain	(K)	30
Regulator time constants	(T_1)	0.01 s
	(T_2)	0.02 s
	(T_3)	0.2 s
Torque limit	(T_{max})	1.1 pu

Parameter		Value
Engine time delay	(T_d)	0.024 s
Actuator time constants	(T_4)	0.25 s
	(T_5)	0.009 s
	(T_6)	0.0384 s

Appendix C: Diesel generator verification

Verification against reference engine model

Table 5: Diesel generator governor model verification results against reference model

Test description	Frequency variation error	
	Transient	Steady-state
Load Step 0 to 30%	0.54%	0.12%
Load Step 30 to 70%	1.20%	0.16%
Load Step 70 to 100%	0.93%	± 0.01%
Load Step 100 to 30%	1.64%	0.14%

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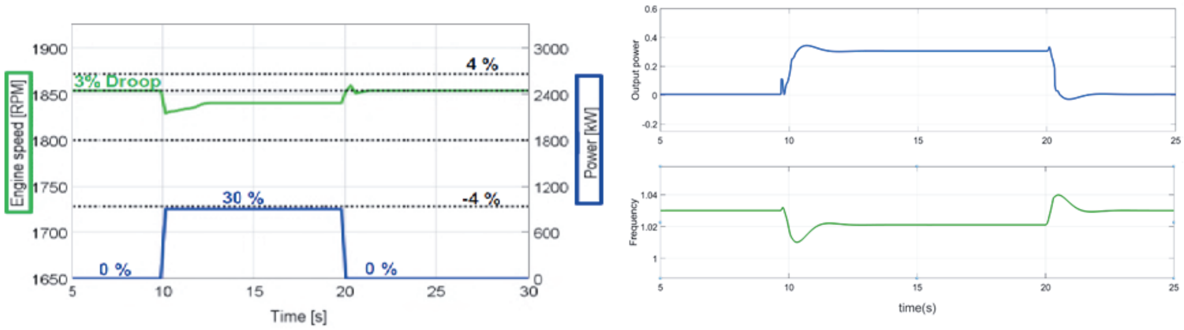
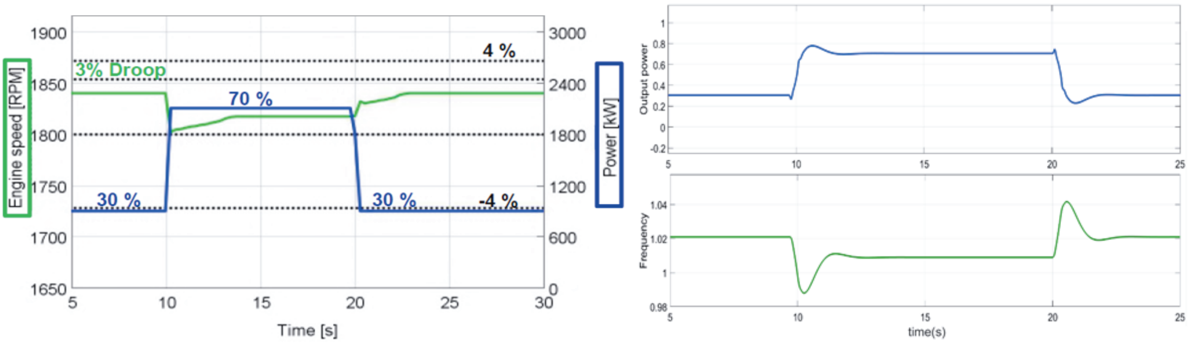


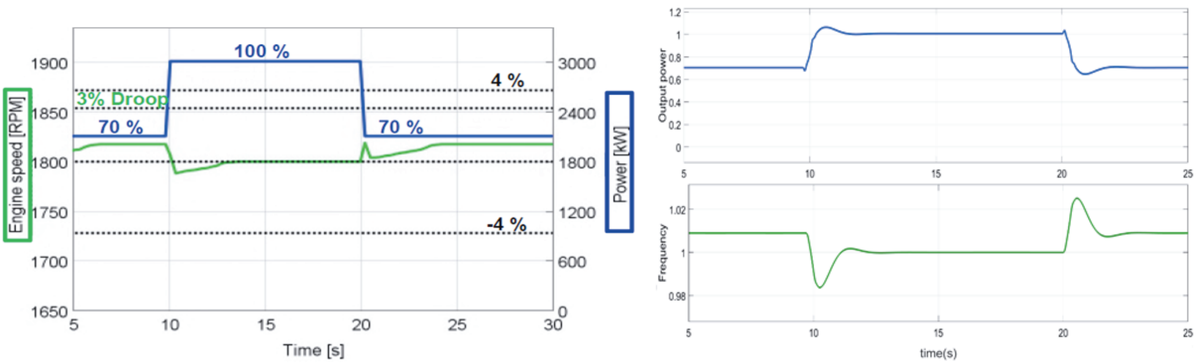
(a) (b)

Figure 7: Simulated results of 0 to 30% load step verification test, showing power and frequency response of (a) the GT-SUITE® diesel engine model, and (b) the proposed engine and governor model



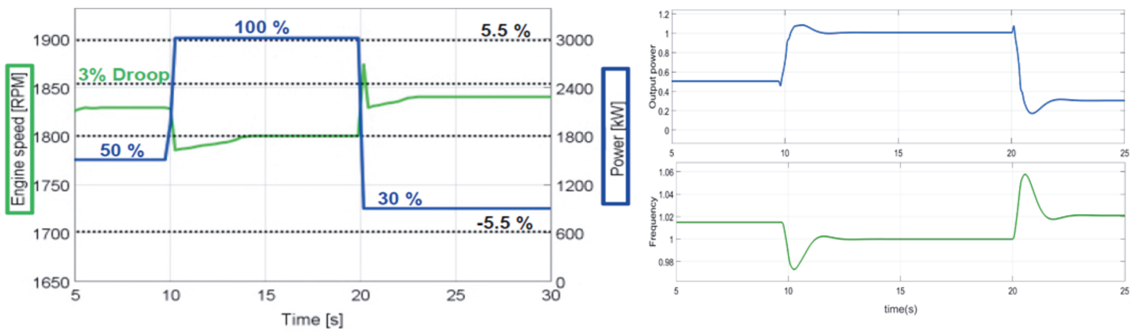
(a) (b)

Figure 8: Simulated results of 30 to 70% load step verification test, showing power and frequency response of (a) the GT-SUITE® diesel engine model, and (b) the proposed engine and governor model



(a) (b)

Figure 9: Simulated results of 70 to 100% load step verification test, showing power and frequency response of (a) the GT-SUITE® diesel engine model, and (b) the proposed engine and governor model



(a) (b)

Figure 10: Simulated results of 100 to 30% load step verification test, showing power and frequency response of (a) the GT-SUITE® diesel engine model, and (b) the proposed engine and governor model

Verification against LRNS performance criteria

Table 6: Diesel generator AVR model verification results against LRNS criteria

Test description	Criteria	Measurement
25 % load, reject 25%	Voltage rise < 7.5%	0.65%
50 % load, reject 25%	Voltage rise < 7.5%	1.45%
75 % load, reject 25%	Voltage rise < 7.5%	1.88%
100 % load, reject 25%	Voltage rise < 7.5%	2.07%

Table 7: Diesel generator governor model verification results against LRNS criteria

Test description	Criteria	Measurement
Load step 0 to 100%	Momentary frequency variation < 10%	- 2.26%
Load step 100 to 0%	Momentary frequency variation < 10%	5.1%
Load step 0 to 100%	Permanent frequency variation < 5%	± 0.01%
Load step 100 to 0%	Permanent frequency variation < 5%	± 0.01%

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