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Design 1

Power System's Dynamic Simulations Supporting Closed Bus Operations

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Abstract

Economic and environmental factors have focused the attention of vessel owners on finding the most efficient way to operate redundant marine power systems. One of the ways to achieve this is using an operational configuration called 'closed busties'. This configuration, although very effective economically, creates fault propagation paths between redundant machinery groups which might lead to a loss of position. This paper discusses power system modelling and transient state analyses as a tool to verify the reliability of the power plant in cases, where live tests performed on the vessel are not sufficient on their own. The advantages of using mathematical models are presented, along with their limitations. Example results from the analysis of semi-submersible unit is presented, which consists of prime mover faults, short circuit faults on main bus, and excitation loss.

Introduction

The integrity of electric power systems in the offshore and shipping industries is becoming increasingly significant due to the growing use of electrical power for propulsion and major industrial systems such as heavy lift cranes, pipe laying facilities, offshore supply and drilling operations. As a result, electrical power systems installed in offshore vessels are growing in both size and complexity. A typical marine power system is divided into two (or more) power plants, depending on vessel type and rule requirements. Dynamically Positioned (DP) vessels of equipment classes 2 & 3 and those vessels with Redundant Propulsion (RP) notation are required to have various degrees of fault tolerance such that a defined amount of generating and propulsion capability remains following single failures which may include complete loss of a compartment to the effects of fire or flooding.

Redundant power systems can be operated as a single connected power system or as two or more isolated power systems. Using several isolated power plants provides isolation and fault tolerance based on passive protection but, increases the number of diesel generators required to run simultaneously in low load conditions which, in consequence, significantly increases gas emission, increases fuel consumption and decreases machinery life. Engine steady state and dynamic performance may also be significantly degraded by low load running.

Operating the power plant as a single connected system, in 'closed busties configuration' using active protection, allows operation with fewer generating units online, with a more economical and environmentally friendly performance. Unfortunately, this arrangement also has the potential to reduce overall power plant reliability and station keeping integrity, by allowing certain failure effects to propagate to all other parts of the power system. If the failure modes, which cause these effects, are not adequately addressed in the design, they can result in full black out of the power plant, or loss of all thrusters and interruption of supply to vital industrial equipment. The integrity of connected power systems relies heavily on the protection system's ability to detect the fault and isolate it, and the ability of all consumers to ride through the failure effects and consequently recover to a steady state.

As a properly designed and verified single power system offers advantages in fuel economy and emission control, there is currently a strong market focus on finding effective tools with which to verify power plant integrity and fault ride through capability.

Obvious tools, which address above considerations, are live tests performed on the vessel in the stage of commissioning. Such tests, if designed and performed correctly, verify the vessel reliability and allow concluding whether the power system is resistant to critical faults. These tests however, are performed in favourable conditions, to reduce the risk of damage to equipment. This limits the severity and range of faults which can be tested this way.

One way to address this limitation is to develop a mathematical model of the power system installed on the vessel and use that to study power plant behaviour in different operational configurations and more severe fault conditions. Power plant modelling is a well-established analysis tool for studying power system behaviour. It has been used by electrical power industry utilities for many years. Most applications are associated with the study of onshore power systems, allowing analysis of system stability, reliability of design, protection strategies etc. There is a significant body of recommended practice available describing modelling processes and providing libraries of equipment models.

The biggest challenge to overcome, when using power plant modelling in offshore applications, is to adapt already existing models to the new environment. Most of the existing models assume existence of connection to vast external network (sometimes referred to as an infinite bus), which is true when operating onshore. Offshore units are operating in island mode, in which the control methods of frequency and voltage differ from those used in onshore applications. Also, the voltage recovery process after severe faults like, for example short circuits, is different, due to lack of existence of external network. Another issue to be addressed is that prime movers used in onshore utilities are often steam turbines, which are widely described in literature. There is, on the other hand, very little research on proper modelling of diesel engines, which are primarily used as prime movers in offshore applications. Overcoming these challenges is crucial to ensure reliable analyses of marine power plant.

Modelling

The, modelling work presented in this paper was performed using the DigSILENT PowerFactory software. This tool allows the user to perform most common analysis, including load flow studies, short circuit calculations, harmonic analyses or motor starting calculations. More importantly, it allows dynamic calculations to be performed, which allow studies of power plant behaviour in the time domain. PowerFactory is commonly used for studies of onshore installations and contains vast library of standard models. It allows modifications of these standard models in its own programming environment, which allows their adaptation to offshore conditions, as well as implementation of bespoke models, tailor made for specific analysis.

The process of modelling starts with entering the electrical power plant data for the specific vessel. Starting with electrical power plant layout, through electrical parameters of equipment installed on the vessel, ending with settings of protection and automation devices. The level of details required for modelling depends on the kind of analysis to be performed. Equipment which is known to have negligible impact on the results can be omitted to reduce model development time and groups of similar equipment can be aggregated and represented as a single component.

The challenge to be overcome at this stage of the process is to acquire sufficient equipment data for the modelled vessel. This is often not possible at this stage and can result in many assumptions being made. These assumptions are based on established good practice and experience. These assumptions, along with simplifications mentioned earlier, all influence the accuracy of results of the analysis. These early models are suitable for steady-state analyses such as load flow, steady-state short circuit analyses, harmonic studies etc.

Performing dynamic transient state analyses requires implementation of controller models such as automatic voltage regulators and governors for installed power generation equipment, power management systems, and any advanced protection schemes for the vessel (e.g. AGP, AGS, DGMS). The scope of the analysis determines the range of systems to be modelled based on knowledge of those which influence the behaviour of the power plant in each operational state.

Voltage and frequency regulation processes, controlled by AVRs and governors, are performed continuously and influence every possible simulation case. Therefore, these systems must be implemented in every application.

Automatic voltage regulators (AVRs) can be modelled using recommended practice provided by the IEEE [1]. One of several pre-prepared and described models can be implemented which is appropriate to the operating principle of the AVR to be modelled. Each model, described in IEEE recommended practice document, is developed for onshore applications. These models assume that the generator, controlled by the device, is connected to external grid. Thus the model assumes that the voltage level is instantly rebuilt means that after any fault, which causes a significant drop on the machine (e.g. short circuit). This is not the case in offshore and marine applications. Additional blocks, which represent devices which aid the voltage rebuilding process, must be added to the standard model, to appropriately represent the voltage behaviour post fault. This is crucial to confirming the ride through capabilities of the vessel's power plant.

Governor models are usually implemented along with prime mover models. There is a wide range of standard models for steam, gas or water turbines, but very few diesel engine models. The most popular and commonly used model for a diesel engine governor is DEGOV, developed for Woodward governors. This model is suitable for marine applications as the model accurately represents the behaviour of prime mover in relevant cases.

When the analysis requires it, there is a possibility to implement additional integrated control systems which influence power system behaviours, such as power management systems or advanced protection strategy systems. To achieve this, the simulation tool used for analysis needs to have the functionality to implement custom models. Developing these systems is a challenge in itself, as each consists of several subsystems, often communicating with each other, and they are commonly tailor made for a specific vessel.

Example Analysis

This paper presents an example analysis of the pole slip phenomenon. Pole slipping of a synchronous machine occurs when the rotor electromagnetic field rotates asynchronously with respect to the stator electromagnetic field. This might occur for several reasons, including short circuit, machine excitation failure or diesel engine mechanical failure. Pole slipping is a rare but dangerous phenomenon, as the synchronizing torques induced cause high current flows and oscillating torques to be developed on machine shaft with the potential for severe equipment damage. Pole slipping is often overlooked as a potential failure mode in some DP system FMEAs.

The example power system chosen for analysis is a semi-submersible unit, with four high voltage switchboards, connected through transfer cables with circuit breakers on each end. For the purpose of this analysis, these circuit breakers are closed to simulate a closed bus operation mode. Single line diagram of analysed unit is presented on

Figure **1**. Each element on this figure represents a model of specific device. The modelling of variable speed drives has been simplified in this case, and loads connected to low voltage switchboards are aggregated and represented as single devices, which behave similarly to group of components they are substituting.

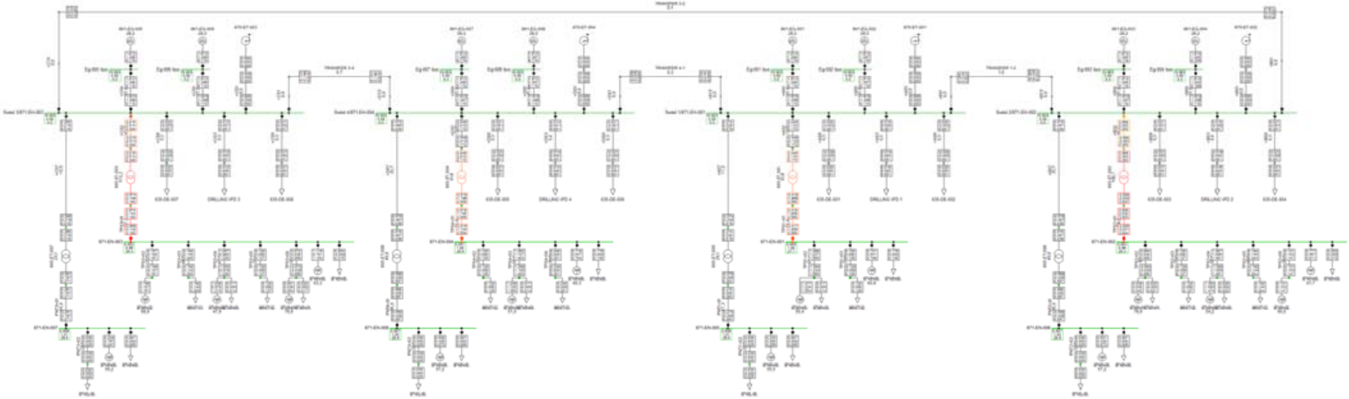

Figure 1 Single line diagram of analysed power plant.

Each of the eight generating sets modelled in this power plant is controlled by an AVR and governor. The AVR model is created using the AC8b standard model from IEEE recommended practice as a base, with changes to equipment relevant to the voltage rebuilding process. The governor model used for this analysis is DEGOV model representing a Woodward governor and its associated diesel engine driving the alternator.

For purpose of this analysis, advanced blocking-based zone protection system has been modelled to allow communication between protection devices installed in the system. This allows proper reaction of the protective functions, which only isolates the region which is subject to the fault. The model of the protection system consists of slightly modified models of protective devices with additional custom made models for communication between them. The operational scenarios used for analysis, which define the loading of installed equipment, are different throughout simulation cases to represent conditions in which the subjected fault might occur.

Short circuit simulations

A short circuit is the unconstrained flow of electrical current. It might be caused by the failure of electrical insulation or any accidental damage which causes electrical conductors to come into contact with each other. The most severe case is shorting 3 phases together, resulting in flow of highest currents.

Short circuit faults create a severe voltage drop (virtually zero volts) at the faulted location. This causes dispersion of electromagnetic fields stored in rotating machines operating in the power plant, resulting in high current flows from them to the faulted location. During the short circuit, these machines gain or lose rotational speed, depending on their operating point prior to the fault and their inertias. Such faults can be easily detected by adequate protection devices due to high currents induced. The protection devices are able to isolate the faulted area very quickly, before the current flow can cause severe damage to equipment.

Figure 2 presents the behaviour of the alternator during short circuit on high voltage switchboard, simulated on the power plant described above.

The short circuit occurred on the high voltage switchboard. After 150 milliseconds, the transfer breaker was tripped due to proper operation of protection device. The faulted switchboard was isolated, and alternators connected to it were tripped in one second due to operation of their overcurrent protection. What is more interesting is the behaviour of the power system components remaining in operation. To satisfy requirements for fault tolerance, the surviving equipment should regain full operability and ride through the fault. Figure 2 presents the behaviour of one of the alternators which remained in operation. As all of the alternators are of the same type and were operating with same load, their behaviour is similar in this simulation. The voltage plot is at the top of the figure and clearly shows the voltage dropping almost to zero followed by the voltage rebuilding process. Below the voltage plot is the current plot. This plot shows the sudden short circuit current and overcurrent state during the voltage rebuilding process (re-energizing electromagnetic fields in rotating machines). The speed of the alternator is also presented, and shows a sudden increase post fault, due to the drop in loading torque, until the machine governor is able to react and stabilize the process.

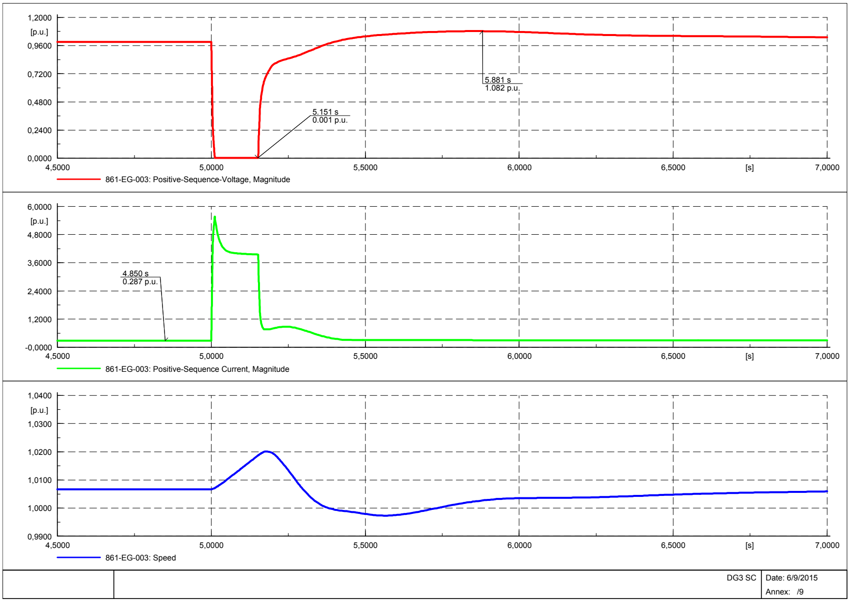

Figure 2 Alternator parameters during short circuit on high voltage switchboard

This figure confirms the ride through capability of the power plant in response to a short circuit fault but the validity of this statement is limited to this particular fault location and this particular operating scenario. It allows the analyst to conclude, that some other cases are also fault tolerant but confidence in extending that assumption to very different operational scenarios could be low. Performing simulations has a clear advantage over live tests, because they allow testing of several different scenarios, with modest effort and no stress on the actual power plant.

Model based simulations allow the analyst to change the operational configuration of the vessel freely to analyse a wide range of likely configurations and operating conditions.

The next figure also presents the short circuit fault on the same switchboard but with different operating scenario. Preforming this type of test carries greater risk of equipment damage than short circuit testing and thus is typical of the types of scenarios that are better investigated using a validated mathematical model. In this scenario, a hidden fault in protective device is simulated, allowing a second barrier to clear the fault. This combination of single failure and hidden failure prolongs the fault clearing time from 150 milliseconds to 600 milliseconds. Also, prior to the fault, the vessel was operating in asymmetric load sharing mode, causing one of the alternators to be much more highly loaded than the others.

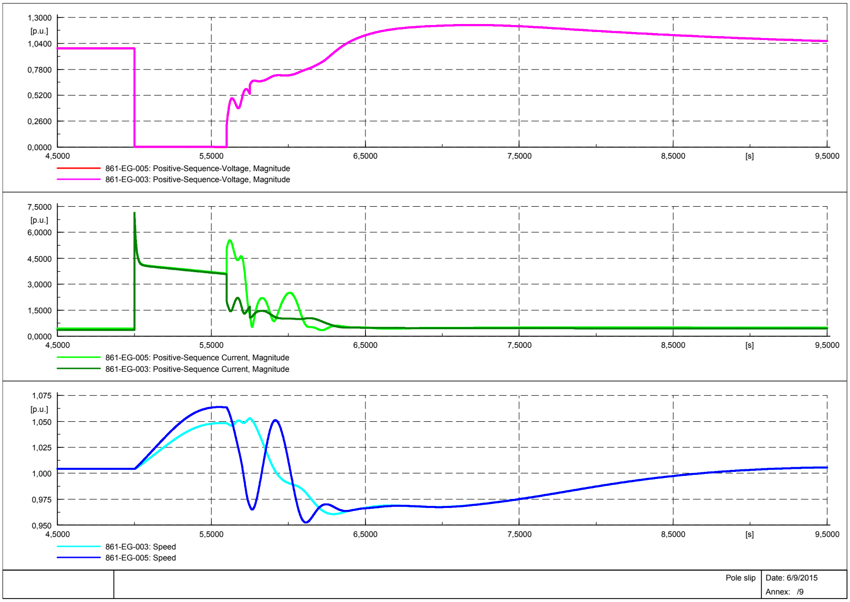

Figure 3 Alternator parameters during short circuit on high voltage switchboard

In this case, the different operating conditions of alternators connected to the grid prior to the fault cause the speed of the shafts to develop differently throughout the short circuit state. The speed difference creates deviation of the rotor angles at the moment of fault clearing. This effect is presented on Figure 4, on which the upper plot presents the rotor angles of the machine operating in asymmetric load sharing prior to the fault (red plot) and the rotor angles of remaining machines (orange plot). After the fault is cleared, the angle discrepancy causes the synchronizing torques to appear, resulting in a high current (shown in light green on Figure 3) and oscillating torques which stressing the alternator shaft and couplings (shown in light green on Figure 4). These kinds of effects are potentially destructive to the equipment but may occur in real fault situations on board vessels.

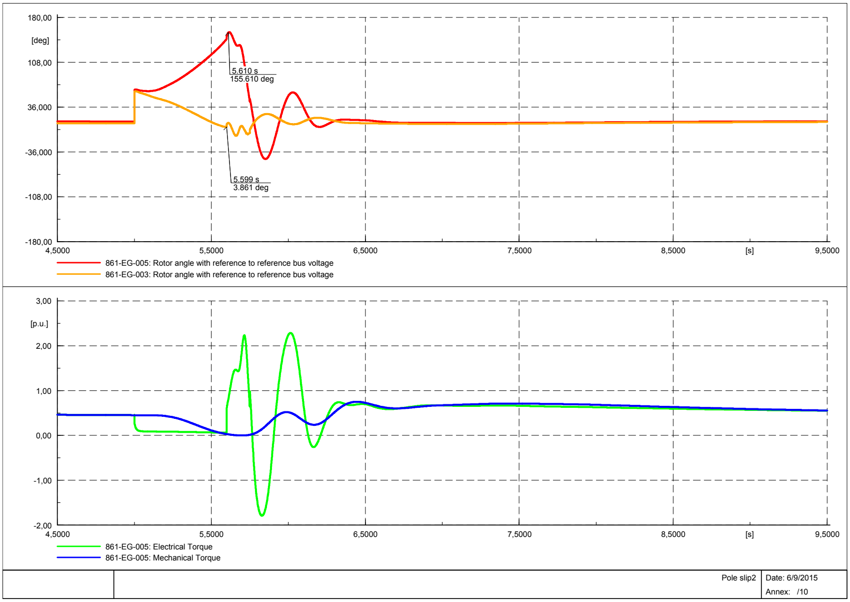

Figure 4 Alternator parameters during short circuit on high voltage switchboard

Prime mover mechanical failure

Severe mechanical failure of a prime mover is another example of a failure mode that is not easily investigated by live testing. Such faults are rare in well maintained power plant but have occurred. Such failures are typically prevented by detecting the onset of critical engine conditions such as low lubricating oil pressure or high jacket water temperature and disconnecting the generator before a more serious fault develops. Should the protection fail to disconnect the generator before the mechanical failure occurs the faulty generating set, becomes a load, which must be fed from other operating DGs. If the mechanical failure is severe, the resulting forces might alter the rotor angle enough to break the electrical bond between rotor and stator. This could result in what is known as a 'pole slip' which creates synchronizing torques which cause severe damage to equipment with the potential for failure effects of a severity exceeding the vessel's worst case failure design intent.

There are major mechanical faults however, which might cause almost instant deceleration of the alternator shaft. Such a fault was simulated in the presented case as a sudden drop of prime mover torque in the governor model. Figure **5** Faulted alternator parameters during severe mechanical fault of diesel engine.Figure 5 presents sample plots of faulted DG behaviour. The sudden speed drop can be observed on the lowest plot (pink). The sudden stop of this alternator would most probably cause very severe damage to the shaft, leading to breakage of the coupler, but the greatest concern in this situation, is to not allow the fault to cause total blackout of the power system.

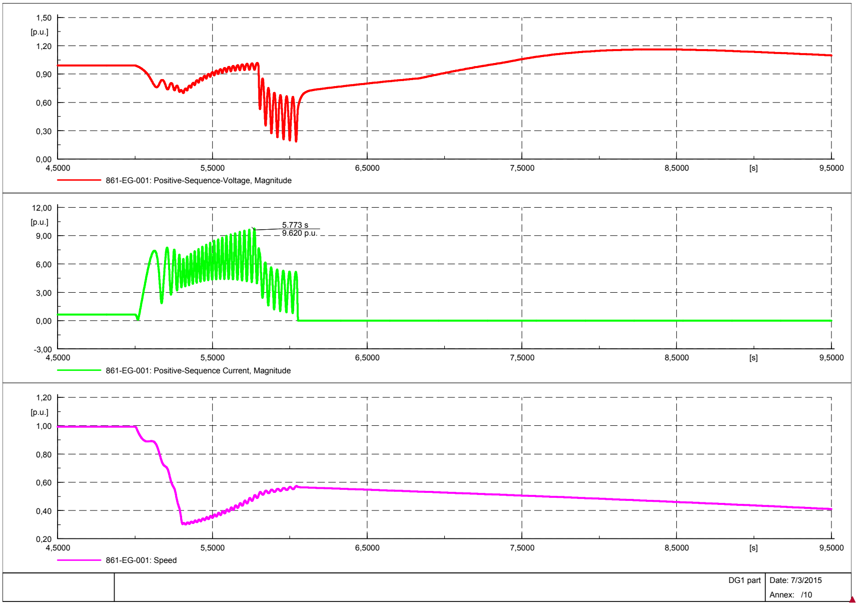

Figure 5 Faulted alternator parameters during severe mechanical fault of diesel engine.

Very high current values induced in this situation, which result from the angle discrepancy, equal or even exceed the short circuit currents. Therefore, the short circuit protection device detects these high currents and trips the bus ties after an appropriate time setting. This current magnitude oscillates along with consequent 'pole slips' – these are the moments that the poles of the machine rotor pass through the field poles. This effect can be observed on Figure 6 which presents rotor angle in reference to bus voltage and the torques influencing the machine shaft (red – electromagnetic torque resulting from synchronizing forces, green- mechanical torque resulting from damaged diesel engine and subsequent coupler breakage). The plot presenting behaviour of healthy DGs is presented on Figure **7**. The high currents which are induced in the faulted machine come from the group of healthy DGs, so the current is divided proportionally. Therefore, much lower current values can be observed on the healthy alternators. After the faulted machine is disconnected from the grid, the stable state is restored by the operation of the machine controllers.

The only non-destructive method of assessing the reaction of the power plant to an event of this severity is by conducting a simulation study. When a validated model is used the results should help to confirm the proper operation of the protection system, or enable conclusions to be made about required changes.

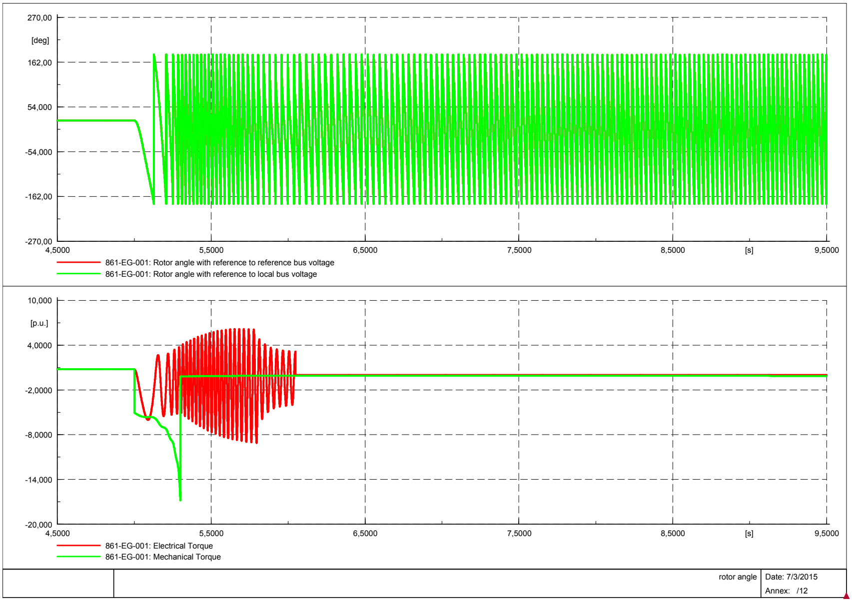

Figure 6 Faulted parameters during severe mechanical fault of diesel engine.

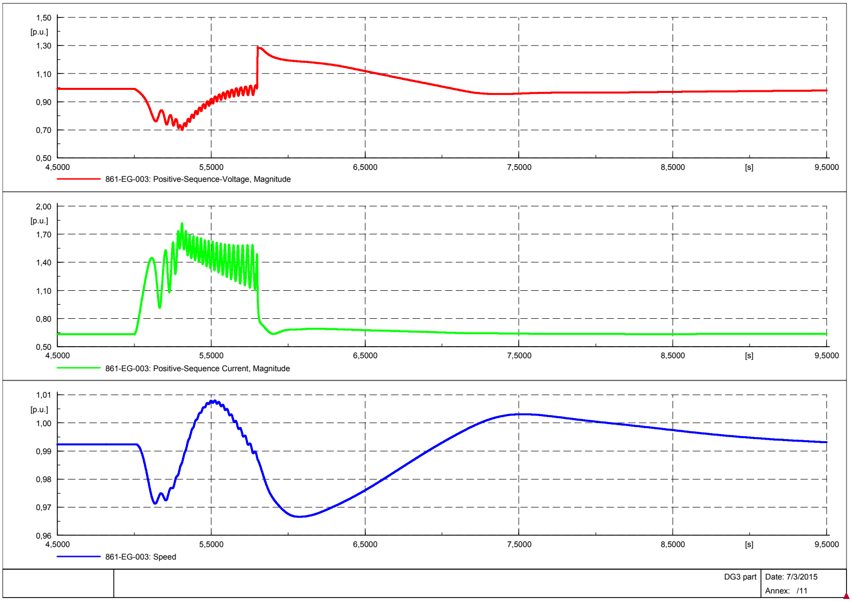

Figure 7 Healthy alternator parameters during severe mechanical fault of diesel engine.

Summary and conclusions

Power system modelling brings much utility and flexibility to the analysis of power system behaviour and allows the analyst to investigate a wide range of fault types. It allows analysis of fault cases, which are not suitable for proof by live testing due to the higher risk of equipment damage in certain fault types. Modelling also allows a reduction in the number of live tests required to provide the necessary level of confidence in the power plant's behaviour. The accuracy of the mathematical model can be confirmed by using it to successfully predict the outcome of a limited range of live tests and test results can be used to further improve the model by providing more accurate data on machine characteristics. This hybrid approach to proving fault tolerance is well suited to the analysis and verification of 'closed bus' configurations, as it allows designers investigate failure effects with reasonable confidence before live testing is carried and use the validated model with greater confidence thereafter. Thus is possible to take remedial action and adapt the design in advance of potential problems to avoid compromising the reliability of the electrical system. Models also allow for the implementation of additional features in power management systems, based on calculation and decisions made during the simulation process.

This however is not the full extent of the potential behind power system analysis. Once the model is created it can be used to investigate and optimise the protection philosophy and allows the analyst to perform simulations on many different systems configurations thus creating the possibility to test different technical solutions and chose the most suitable ones. This facility is useful in the design phase of newbuildings, and when planning life extensions and retrofits for vessels already in service.

Nowadays, more and more complex management and protection systems are developed in order to provide optimal efficiency and reliability in power plants. The more complex such systems become the harder it is to predict the behaviour of the power plant in all its various configurations and fault cases. Performing simulations allow verification of protection performance in different operational scenarios, and coordination with other integrated systems installed on board is possible. Development of this branch of analysis is an important part of creating future verification tools for a whole range of vessel types. In particular, vessels with class notations requiring fault tolerance in power plant design such as DP and RP.

References

[1] IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, 2006