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Lessons learned from power system’s dynamic simulations supporting closed bus operations

By Artur Zbroński

DNV

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 goal 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. On DP Class 3 vessel, this configuration requires special considerations for confirmation of power system reliability and robustness in addition to tests.

Classification societies required power system dynamic simulations as one of such tools for several years. This paper presents lessons learned from such simulations performed on various mobile offshore units and vessels. Presented examples show ability of the transient simulations to perform verification in more depth than testing or desktop analyses allow. Lessons learned range from protection system coordination issues to configurations allowed during DP Class 3 operations.

The article aims in finding an optimal, proven methodology of power systems verification using computer simulations, which provide time and cost saving results, besides variety of potential scenarios considered.

Abbreviation / Definition

APSP – Advanced Power System Protection
AVR – Automatic Voltage Regulator
CB – Circuit Breaker
DG – Diesel Generator
DP – Dynamic Positioning
HVSB – High Voltage Switchboard
RP – Redundant Propulsion
WCFDI – Worst Case Failure Design Intent

Introduction

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.

Classification societies indicate that when the 'closed busties configuration' is to be considered for the vessel with DP class 2 or 3 notation, analysis of equivalent integrity should be performed (1,2,3,4,5,6). There is a strong 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 digital twin to study power plant behaviour in different operational configurations and more severe fault conditions than the tests allow. Structured guidance documents which present the approach for using the above-mentioned method exist (6,7) but are not commonly used by all classification societies.

The author of this paper was involved in a number of analyses to show equivalent integrity for closed bustie configuration vessels. The following chapter presents the lessons learned from the performed analyses.

Lessons learned

One of the things to consider when planning the simulation analysis is to choose proper simulation cases. While the general specifications of the analysed scenarios are given in guidance documents, (6,7) there are some simulation cases which are not commonly considered which are nevertheless worthwhile to analyse.

The commonly addressed failures which are indicated to be analysed in the simulation study are the following:

- Short circuit and earth faults
- Crash synchronisation faults
- Load acceptance and rejection
- Pole slip

Advanced Power System Protection

The APSP (Advanced Power System Protection) systems, which, among other functions, provide means to detect the faults resulting in active/reactive power sharing imbalance, are often considered proven as reliable through desktop analysis. The problem arises, when the system is supposed to identify the device subjected to fault, when the power plant is operating with 2 DGs online in closed bus/ring configuration. The load sharing imbalance in those cases is caused by a fault in AVR or an engine governor, which are responsible for reactive and active power control respectively. In configuration with 2 DGs in operation, a fault in one of them will cause the healthy one to also react in an opposite direction. Differentiation between them is done basing on the dynamic behaviour of the power plant following the fault.

An example of the fault which would be detected by APSP system is presented on *Figure 1* and *Figure 2.* In the presented example, where 3 redundant power systems operate in closed bustie configuration, with 2 DGs operating in parallel, the fault is fuel rack malfunction on one of the operating DGs. The APSP systems task is to properly identify the fault and the faulty DG. In order to do so, two parameters should be observed, i.e. active power levels and the frequency. While the active powers of the DGs would stay at the same level, assuming constant loads for simplicity, the frequency and therefore DG speed, would be initially forced out of equilibrium by the fault. The direction of the change dictates the nature of the fault, and in combination with the active power level of DGs properly identifies the faulty DG which is subsequently disconnected.

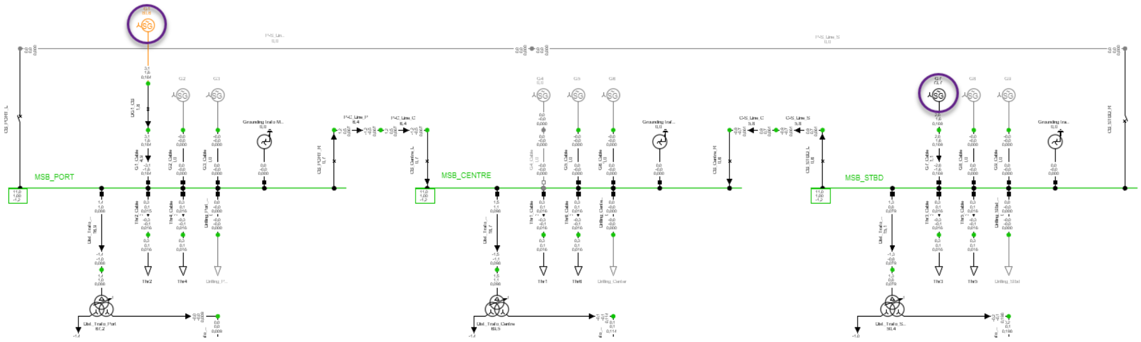

Figure 1 Power plant single line diagram – 3 redundancy groups connected in closed bustie configuration, 2 DGs online: DG1 (yellow circle), DG7 (purple circle). Fault - Stuck fuel rack on DG1.

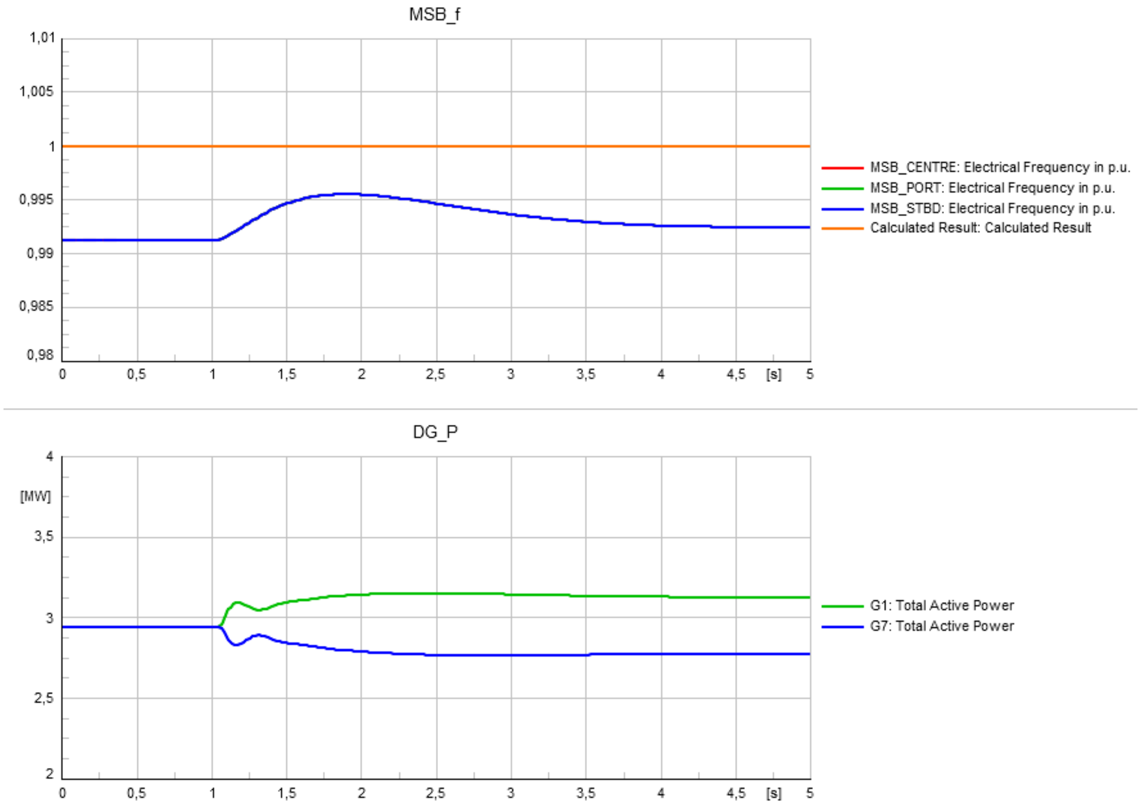

Figure 2 Power plant single line diagram – 3 redundancy groups connected in closed bustie configuration, 2 DGs online: DG1 (yellow circle), DG7 (purple circle). Fault - Stuck fuel rack on DG1.

The problem lies in detection of the frequency change, since after the initial transient change, the healthy controller brings the signal back to the setpoint level, as presented on *Figure 2*. Therefore, the threshold for the detection should be set on the level to detect such occurrence without triggering false alarms. In some occurrences, this threshold might be set too high, which is unviable to verify this via desktop study. It is therefore recommended to verify the power plant resilience to the reactive/active power imbalance faults through dynamic simulations.

If a fault like above would be allowed to continue without detection, it could lead to a pole slip condition.

Pole slip

One of the controversial points on the list of faults to be considered when analysing the fault ride through capability of the vessel is the pole slip "fault". It should be considered that this phenomenon is not a fault in itself, rather a consequence of another fault, such as a prolonged short circuit fault in unfavourable conditions, crash synchronisation event or severe mechanical fault of the diesel generator set.

While not precisely defined in the guidance documents, this phenomenon should not be taken lightly, and is indeed possible to occur when proper precautions are not in place. One of the easily overlooked scenarios which could lead to this occurrence is the asymmetrical load sharing mode, during which one of the DG sets is running with high loading in order to clean the carbon waste accumulated in the cylinders during the low loading operation. This forces the other operating DG sets to operate with lower loading levels.

If the short circuit fault occurs during such operational mode, the DG sets start to "free wheel", loose synchronism and start to develop different speeds, depending to the loading level at the moment the fault occurred. Different speeds lead to difference in rotor angles, which can accumulate to extreme values before the fault is cleared by the protection system. The example of such occurrence is shown on Figure 3 and Figure 4.

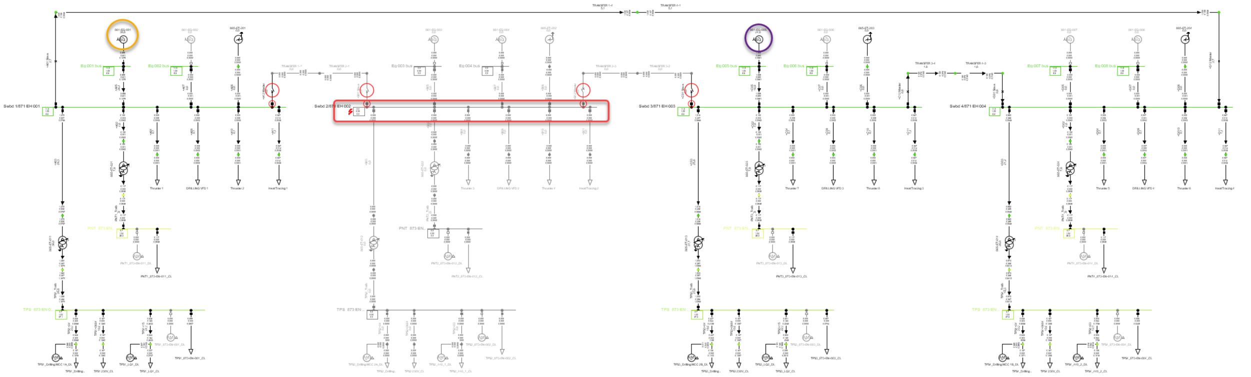

Figure 3 Power plant single line diagram – 4 redundancy groups connected in closed ring configuration, 2 DGs online: DG1 (yellow circle), DG5 (purple circle). Short circuit fault on HVSB 2.

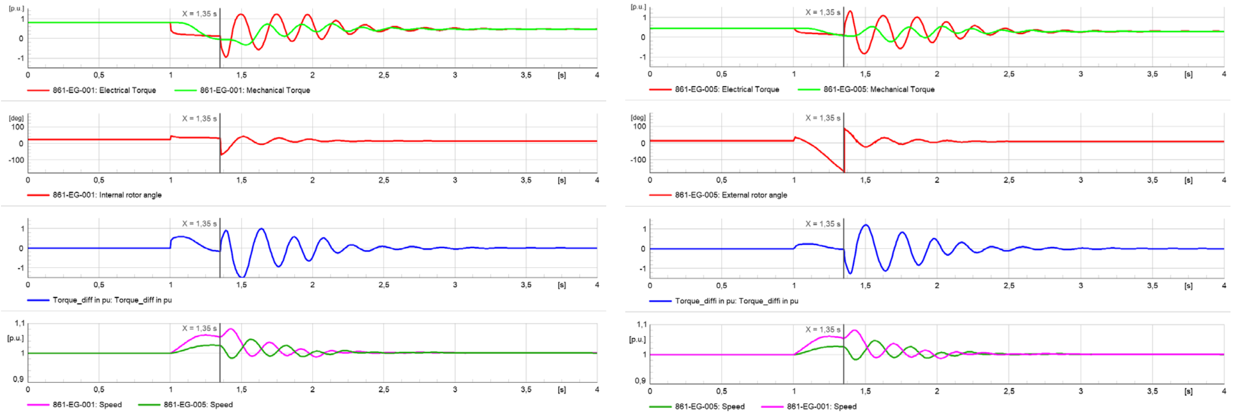

Figure 4 Parameter behaviour plots for DG1(left set of plots) and DG5 (right set of plots) – electrical and mechanical torques (red and green lines in the top plot, respectively), rotor angle (red line, second plot), torque difference (blue plot), DG rotational speed (pink and green lines).

The operation scenario is a power plant with four redundancy groups operating in closed ring configuration with 2 DGs online during asymmetrical load sharing mode, where DG1 is operating with 80% loading, while DG2 is operating with 45% loading. The fault is 3 phase symmetrical short circuit on HVSB2, as marked on Figure 3.

Even though the fault lasts for a relatively short duration until it is cleared by the protection system, the difference in speeds developed during the fault, as shown on Figure 4, leads to a pole slip condition, where one of the DGs performs a full additional rotation in relation to the other DG. The fault is cleared when the rotor angles of the DGs are in opposition to each other, leading to worst possible case for synchronisation. The resulting synchronising torques and currents are high in amplitude and oscillating rapidly, putting significant mechanical strain on the equipment and in most likelihood loss of the power plant and DP capabilities of the vessel.

Described situation could occur in all power system where asymmetrical load sharing operational mode is utilised, independent on number of DGs in operation or closed bus/closed ring configuration. It is strongly advised to avoid using that operational mode during DP operations.

In addition to the asymmetrical load sharing mode, the same phenomenon and observed behaviour is applicable to the systems with DGs of different ratings connected to the common power plant and operating in parallel. Depending on the difference in ratings and relative loading prior to the fault, the consequences would vary, but the same cause-effect chain applies, leading to possible consequences similar to the presented. It is strongly advised to refrain from using DG with different ratings in power systems which are designed to operate in closed busties operational modes.

Negative sequence fault in closed ring configuration

When considering a closed bustie configuration, there are two options for connecting the power plant, closed ring configuration and closed bus configuration as presented on *Figure 5*. Both configurations come with their own pros and cons, and both are viable options to choose from.

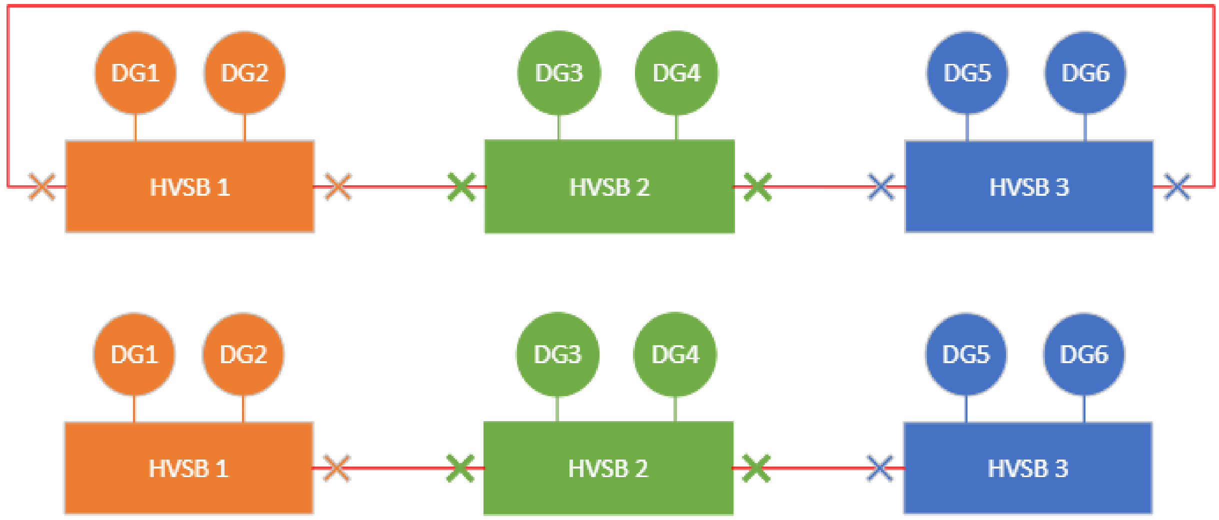

Figure 5 Closed ring configuration (upper drawing) and closed bus configuration (lower drawing)

Interesting phenomenon occurs when considering the closed ring configuration when regarding the negative sequence phenomenon which could occur when one phase is lost in one of the transfers between different HVSBs. The consequent phase imbalance would be felt throughout the power plant, however only in the transfer cables. None of the feeders or incomers in the power plant would detect the fault. If a phase unbalance protection is based on detection of negative sequence component in feeders or incomers exclusively, the undetected fault would be considered a hidden failure, which in combination with other fault could lead to consequences exceeding the Worst Case Failure Design Intent (WCFDI). It is therefore strongly recommended to include the negative sequence component detection in the relays implemented in the transfers when closed ring configuration is considered as a possible operational mode.

Importance of guidance document

The negative sequence protection evaluation discussed above is often not considered in the dynamic simulation report, since the phenomena associated with that fault are not dynamic in nature. There are situations however, when the requirements regarding the scope of the dynamic simulation study are not specifically defined and do not follow the commonly available guidance documents.

I was involved in one study, in which the customer, driven by classification society requirements requested an analysis with very broad requirements. Combining a set of seven operating modes, six failures with different locations and assessment of second barrier to the analysed faults, the analysis contained 272 simulation cases. The report from the analysis spanned across 1300 pages, of which 90% was redundant and unnecessary, and the relevant worst case condition simulations were overshadowed.

It is crucial for the clear conclusions to the reader and the vessel owner to follow a proper guidance document, which list relevant cases to be simulated and a details a process of choosing worst case scenarios to avoid situations like described above.

Conclusion

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 bustie' 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.

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