DP3 Class Power System Solution for Dynamically Positioned Vessels

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Abstract:

Dynamically positioned vessels use electrically driven propellers to keep position during oil & gas drilling operations, station-keeping, anchoring, port maneuvering, etc. One of the requirements for the safe operation of the vessel is that no such faults can occur that may result in significant loss of vessel position.

In marine isolated power systems there will typically be installed relatively low number of generators (4 to 8) where the overall power system will be typically split into 2 to 4 sections and each section typically contained in separate engine room, isolated with fire- and watertight wall. Each generator shall supply power to one or more large electric consumers, e.g. electrical frequency converters (VSD). These engine room sections are connected by bus-ties to allow that any generator in the system can provide the power to any of the consumers e.g. thruster(s) or drilling loads.

It has been well known for number of years, that operation with closed bus i.e. connected sections and sub-sections in different engine rooms, will allow for significant reductions in fuel consumption and running costs of the engines. Operating system with only two engines will allow operation on higher power per individual engine where the fuel economy will be better. Depending on the vessel operational profile and current operational philosophy, the closed bus mode may allow for up to 5% of fuel savings per year. Reductions in the maintenance costs of the engines may also be very significant, i.e. 30% or more.

The disadvantage of running the system in closed bus interconnected mode may make system more varnouble to faults, so any fault e.g. short-circuit or generator failure may make a total vessel blackout. This paper presents the technical solution of fault tolerant power system, able to cope with high integrity against any known fault and failures. This enables the power system to operate with full safety in closed bus / closed ring mode during DP2 and DP3 operations. The technical solution is consisted of following advanced features:

**Advanced short-circuit and earth-fault protection**: special protection relay scheme where maximum possible short-circuit fault detection and fault isolation is accomplished and where several functions are used as a back-up to back-up, resulting in the system that can clear any major fault very fast, and where advanced back-up functionality will allow protection system to operate with minimum delay in any situation;

**Advanced interlocking relay scheme** enabling safe use of the system in remote and local mode, reducing risks of human error;

**Fault isolation per sub-section**: ability to isolate the fault within the sub-section, and allow loss of only one thruster due to single fault;

**Fault ride through capability** off generators: features in generators that will enable system to return to operating point without failure in the equipment;

**Generator Protection Controller (GPC)** – special generator fault detection and fault isolation product, it is based on previously developed product by Siemens called P3. GPC is model based, it has two levels, in basic level 1, it may be supplied as additional back-up, while Level 2 shall cover for more sophisticated faults, more difficult to find

**Fault ride through capability** off essential equipment e.g. thruster VSD: all equipment is designed with special features for maximum fault ride through capability lasting longer than the maximum clearance time needed as defined above;

**Advanced generator adaption (GPA)** – algorithm used in e.g. blackout situation when load on generator becomes suddenly higher than 110% and frequency starts to drop rapidly. By use of
thruster and riling VSDs, GPA will enable fast load adaptation of the generators in less than 100 ms;

Methods to deal with hidden faults: will allow to deal with any hidden fault that was not defined "a priory" or where equipment major protection and its back-up also failed;

Fast power system recovery after blackout; if the blackout occurs, the system shall recover very fast, within 30 seconds.

Extensive FEMA done in order to check all necessary design requirements has been successfully tackled in the power system design. R&D programme within Siemens is focusing in making DEMO/Training/Testing Lab in Oslo, Norway that shall be used to demonstrate the concept to the clients.

1. Traditional and new power system solution for DP3 closed ring

1.1. Traditional power system solution for redundancy and fault tolerance

Dynamically positioned vessels use electrically driven propellers to keep position during oil & gas drilling operations, station-keeping, anchoring, port maneuvering, etc. One of the requirements for the safe operation of the vessel is that no such tripping can occur that may result in significant loss of vessel position, and result in consequent high risk of vessel failure, loss of life, oil pollution, fire, flooding, collusion, and similar.

It has been well known that operation with closed bus i.e. interconnected mode with connected sections and sub-sections in different engine rooms and compartments, i.e. electrically connected bus-ties, will allow for number of advantages, including reductions in fuel consumption and exhaust gas emissions, reductions in running costs of diesel engines and increased flexibility for the DP, i.e. propulsion.

The disadvantage of running the system in interconnected mode, with bus-ties and sections connected may make system more varnouble to faults, so any fault e.g. short-circuit or generator failure may make a total vessel blackout. For dynamically positioned vessel, performing operations with high risk for the vessel, human life and environment, the blackout must be avoided by all means. The worse of the blackout is the loss of vessel position (GPS), with seabed fixed point referenced coordinates. Very important demand for the vessel is the blackout recovery capability. If the blackout occurs, the vessel must recover in the minimum time possible, preferable in less than 30 seconds as this may be more-or-less defined as a critical time for the position loss.

The problem of dangerous fault propagation and consequent loss of total power system functionality resulting in total blackout, or tripping of essential consumers, was solved (referred here as Traditional solution) by operating the vessel with fully segregated power sections i.e. open bus-tie Breakers or so called System Split Mode, typical system split to 2, 3 or 4 power sections in one marine vessel.

With such system split, a fault, i.e. blackout, in one power section will not affect the other power sections(s) and will not lead to possible loss of position of the vessel. Other power sections keep the power supply to consumers and the vessel is be able to keep the position in any situation.
The required mode prescribed splitting the power system to several sections, see Fig. 1.; where each operate individually in its own engine room, segregated by firewall and watertight separation. The vessel was required to operate in this mode during dangerous/risky operations such as drilling, maneuvering, station-keeping and similar. As the DP3 operated vessels is operated with open tie-breakers between the power sections, each power section must have generators running at all time. This is to allow power flow to all thrusters and consumers, ie. drilling. This leads to ineffective use of generators, resulting in increased fuel consumption, increased exhaust gas emissions, increased maintenance costs. This also results in some other negative consequences such as control limitations in DP thrust allocation (load ramping) and potentially reduced propulsion efficiency, higher load fluctuations per generator, etc.

Fig. 1. Example of system with 3 sections (3 engine rooms) where one gen-set must run in one engine room, so failure in one section can not result in loss of total system functionality, i.e. total blackout

1.2. Overview of new fault tolerant power system based on “self sustained islands”

The problem of running minimum number of gen-sets in fully interconnected system with connected power system sections i.e. closed bus-ties is solved by design of enhanced fault integrity system consisted of following advanced features:

Self-sustain islands: Intelligent autonomous power producers and consumers without cross dependency. Due to advanced zonal fault protection scheme, the protection system is able to isolate the fault within the sub-section, and allow loss of only one thruster due to single fault. As there are no cross-dependences, than loss of single sub-section shall not have impact on the rest of the system that remain intact.

Advanced short-circuit and earth-fault protection: special protection relay scheme where maximum possible short-circuit fault detection and fault isolation is accomplished and where several functions are used as a back-up to back-up, resulting in the system that can clear any major fault very fast, and where advanced back-up functionality will allow protection system to operate with minimum delay in any situation; With respect to above, detailed design of protection system has been performed considering opening time of breakers, relay respond time with Furrier fast transformation algorithms for harmonic calculation and inrush restraint, relay pick-up time, relay drop-out time. Detailed studies have been done to dimension the current transformers (CTs) and avoid saturation, and CT accuracy is carefully selected. Communication capabilities of the protection scheme have been continuously tested within IEC 61850 protocol in the lab during the development of the system.
**Voltage transient mitigation:** allows for sensitive fault protection and smooth operation of the power plant; two methods have been implemented: 1. soft voltage build-up on AVR allows generator to recover voltage in 5 seconds and pre-magnetize all connected consumers (transformers) without inrush thus avoiding transformer saturation due to fast flux recovery and 2. Design of Pre-magnetizing circuit for the transformers with synch-check capability implemented inside protection relays (Siprotec). With respect to these methods, extensive number of studies has been performed for estimating the transformer inrush.

**Advanced interlocking relay scheme** enabling safe use of the system in remote and local mode, reducing risks of human error;

**Fault ride through capability of generators:** enable system return to operating point without equipment failure; With respect to fault ride through and relay protection, number of short-circuit studies has been performed on number of project and detailed data collected for generators, AVR, governors, engines.

**Generator Protection Controller (GPC)** – special generator fault detection and fault isolation product, it is based on previously developed product by Siemens called P3. GPC is model based, it has two levels, in basic level 1, it may be supplied as additional back-up, while Level 2 shall cover for more sophisticated faults, which are more difficult to detect.

**Fault ride through capability** off essential equipment e.g. thruster and drilling VSD: all equipment is designed with features for maximum fault ride through capability. Kinetic recovery during the fault ride through is able to keep the VSD operational during longest fault/short-circuit scenario.

**Advanced generator adaption (GPA)** – algorithm used in e.g. blackout situation when load on generator becomes suddenly higher than 110% and frequency starts to drop rapidly. By use of thruster and drilling VSDs, GPA will enable fast load adaptation of the generators in less than 100 ms;

**Methods to deal with hidden faults:** will allow to deal with any hidden fault that was not defined “a priory” or where equipment major protection and its back-up also failed;

**Fast power system recovery after blackout:** if the blackout occurs, the system shall recover very fast, within 30 seconds.
Fig. 1.2. Example of system with 3 sections (3 engine rooms) and 2 sub-sections per section - Fault integrity is based on: Limited amount of interconnections on lower level distribution and advanced protection scheme on top level; the system is able to clear the fault fast and with high accuracy, and is able to isolate the fault on single sub-section resulting in loss of only one thruster and/or one genset. This will allow vessel to operate with interconnected power system sections i.e. connected bus-ties, where only 2 gen-sets can be running online so if failure in one section shall not result in loss of total system functionality.

2. Design principles for DP3 closed ring

2.1. Overall Design Targets

The overall design target is to create an economical, reliable and efficient power plant/power distribution system, which includes:

- Efficient operation of the rig with minimum fuel consumption and exhaust gas emissions.
- Operation of the unit power plant with closed tie-breakers. (DP-3 with closed tie-breakers).
- Fault-ride-through capability for equipment and systems.
- Fast start-up (< 20 seconds) for power generation, distribution and thruster drives in case of a power blackout.

Main headlines in the design are:

- Intelligent autonomous power producers and consumers without or limited cross dependency
- Inrush and transient stress in the system has been reduced or removed
- Fast restart and reconnection of drives and motors
- Automatic isolation of faulty equipment.
- Main SWBD communication between protection devices by IEC 61850.
- Grid (voltage and frequency) used as communication device – Generator Performance Controller (GPC) self-sustained diagnosis within each generator cubicle.
- High reliability and availability of all systems and products.
- Redundant UPS power supply to all vital consumers.
- Remote diagnostics and service assistance.

This is achieved by the following key design objectives:

**Increased reliability and monitoring of the main distribution**

- Tie cables between the main switchboards to be protected for mechanical impact, fire and flood.
- Fire and flood monitoring should also be included in the cable compartments for the tie cables.
- Fully insulated phases in the complete ring, i.e. use of single core tie-cables will reduce the possibility for a phase to phase cable fault
- Use of fixed mounted circuit breakers in the main ring will reduce the possibility for a faulty connection, i.e. bad connection in a tulip contact as used in withdrawable circuit breakers

**Component Selection**

- Use more capable, programmable devices immune to voltage and current distortion and transients, able to be programmed fast and reliable, using IEC 61850 and Profibus DP communication protocols.
- Intelligent devices facilitate uniform process software and rapid restoration of default parameters after a fault.
Reduced Interdependence
- Removes central communications infrastructure, allows autonomous machines.

Reduce "Normal High Stress Transients"
- Pre-magnetize transformers and capacitors to eliminate inrush loads.

Improved Monitoring
- Select intelligent devices with self-diagnostic capabilities for early detection of faults
- Utilize bus voltage and frequency as primary power management system interface between units
- Utilize PLC for GPC as main interface (Gateway) between Switchboard communication on IEC 61850 and Power Management System communication on Profibus DP. Due to redundancy and principle of self-sustained system, one PLC gateway to PMS is dedicated per each of the generators.

Distribute Intelligence to Loads and Generators
- Sense bus condition by voltage and frequency.
- Load shed and power limit based on bus frequency.

Thruster auto-start based on bus condition
- Split Bus Into Independent Power Systems prior to fast start up of frequency converters.
- When generator goes into over-current, open tie breaker prior to trip.
- When bus frequency or voltage is out of tolerance, open tie breaker.

2.2. Self Contained Power Cells

The power cells (generators & switchboards) shall be made self contained, they shall have their own support systems handled by the power cell alone. By utilities are here meant systems needed for the operation of the power cell like HVAC, fuel oil system etc.

![Figure 2.1 – Power Cell Interfaces](image-url)
This does not imply that there will be as many systems as power cells, but the design target can be handled by intermediate storage (e.g. fuel oil day tanks) or shared systems with redundancy designed according to DP-3 rules handling fire & flooding.
For further details one has to refer to typical P&ID's.
It is of vital importance that common systems like ESD and F&G is designed not to negatively influence the design target. (E.g. normal de-energized output instead of energised outputs etc.)

2.3. Intelligent Producers & Consumers

The power system shall be divided into “function islands”, which performs autonomous and intelligent control and monitoring. By adding specific and autonomous control the generators and its supporting equipment can be considered as “intelligent producers”, and the drives including its supporting equipment can be considered as “intelligent consumers.”

For the thrusters the 11kV breaker, transformer, drive, thruster motor and thruster utilities function as one functional unit.
3. Advanced protection system

For a DP Class-3 vessel the normal operating mode by the classification society e.g. DNV is with open tie-breakers. To achieve proper protection and segregation when operate with closed bus-tie/coupler breakers, additional protection units have to be included.

A zone concept with differential protection and sensitive directional fault protection has been introduced. Within each zone there are several producers and consumers with different rating and functions. The protective ZONES for the system are shown in Figure below for one indentified sub-section which is consisted of 1 generator, 1 thruster and one consumer either: drilling drive feeder or distribution feeder. Other 5 sub-sections are mirror copy of this one presented.

Following main protection functions are used (among number of other functions):

- 87 (ANSI code) – differential current protection
- 67 (ANSI code) – directional current protection: with feeder blocking (rev. interlock from feeder) - Directional protection is set without any delay, no time grading. This is to assure complete redundancy to 87 protection.
- 50/51 (ANSI code) – conventional short circuit and definite time over-current curves
- 50BF (ANSI code) – circuit breaker failure function – logic to implement if any circuit breaker fail to trip and fault (high) current measured after the time to clear the fault elapsed

All functions mentioned above are known by mentioned codes in the protective relay terminology.

The value of the solution presented in this paper is the system application to dynamically positioned vessels and back-up functionality where minimum clearance times are accomplished.

In addition to sensitive fault and bus differential protection several additional protection functions have been included:

- Shunt Trip Coil Supervision (74TC)
- Switch On To Fault (SOTF)
- Broken Wire Monitoring
- Current and voltage symmetry in the internal measuring circuit
- SF6 gas monitoring – breaker interlock
- Monitoring auxiliary contacts of the breaker etc., ref. next chapter for more details
**Figure 3.1 – Protection zones**

<table>
<thead>
<tr>
<th>Protection function</th>
<th>87</th>
<th>67</th>
<th>50/51</th>
<th>50BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment to protect (ZONE):</td>
<td>Differential zone</td>
<td>Directional (with logic)</td>
<td>OC</td>
<td>Breaker failure</td>
</tr>
<tr>
<td>Generator</td>
<td>MAIN</td>
<td>---</td>
<td>BACK-UP</td>
<td>BACK-UP</td>
</tr>
<tr>
<td>Bus-tie cables</td>
<td>MAIN</td>
<td>BACK-UP</td>
<td>BACK-UP</td>
<td>Relay must trip Bus-tie CB in both sections: master-slave</td>
</tr>
<tr>
<td>Bus-coupler</td>
<td>MAIN</td>
<td>BACK-UP</td>
<td>BACK-UP</td>
<td>If bus-coupler fail then relay must trip next breaker to the left side and one to the right side</td>
</tr>
<tr>
<td>Dist. feeder with transformer</td>
<td>(optional)</td>
<td>blocking BB67 if feeder fault</td>
<td>MAIN</td>
<td>BACK-UP</td>
</tr>
<tr>
<td>Thruster feeder with transformer</td>
<td>(optional)</td>
<td>blocking BB67 if feeder fault</td>
<td>MAIN</td>
<td>BACK-UP</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; winding for thruster utils</td>
<td>(optional)</td>
<td>---</td>
<td>MAIN</td>
<td>BACK-UP</td>
</tr>
<tr>
<td>Drilling feeder with transformer</td>
<td>(optional)</td>
<td>blocking BB67 if feeder fault</td>
<td>MAIN</td>
<td>BACK-UP</td>
</tr>
<tr>
<td>Sub-section</td>
<td>MAIN</td>
<td>BACK-UP Directional BB logic</td>
<td>BACK-UP</td>
<td>BACK-UP</td>
</tr>
</tbody>
</table>

Trip all CB in Sub-section
Feeder protection
Feeder protection is equipped with over-current trip, time delayed and instantaneous short circuit trip and a core-balanced current transformer for earth fault protection. If feeder’s protection doesn’t operate at first time in case of fault, back up protection trips bus-tie/coupler breaker and covered side of bus-bar remains in service.

Inrush Current Detection
All transformers are equipped with pre-magnetization circuits to avoid inrush currents. However, all transformer protection relays has software function (2nd harmonic restraint) to detect inrush current and avoid spurious trips on eventual inrush current. Interesting to notice is that if this function is enabled, relays need minimum 20 ms extra tripping time to differentiate between the fault current and the inrush current. This function has been tested on many applications and its behaviour is known. However, it remain uncertain how sensitive settings can be obtained and if this function will be able to differentiate between inrush and e.g. directional faults when transformer saturate when e.g. fault at secondary. This shall depend on system design and in particular is different for every transformer design e.g. magnetization current and saturation curve. This is the reason for introducing the soft inrush functionalities within AVR and Pre-mag circuit at the MV transformers.

Differential Protection for bus-bar
Bus-bar differential protection for short circuit is provided. The protection scheme is provided that upon a fault, all CBs connected to the faulty bus shall open and isolate the faulty part of switchboard, while the healthy switchboard sub-section remains operational. A lock-out relay is included to prevent closure against a fault.
All relays in the sub-section and section of the switchboard communicate with IEC 61850 protocol.

Bus-tie protection
The bus-tie breakers are equipped with differential current protection, sensitive directional protection, over-current protection, time delayed and instantaneous short circuit trip and differential earth fault and directional protection. A lock-out relay is included to prevent closure against a fault.
Cable differential protection function is implemented in two cable differential protection relays communication with each other by fibre optic cables. By this selection, issues related to fire and flooding will only have local impact and the protection relay on the “other side of the A60 wall” can take all necessary actions.

Directional logic selectivity: 67 (ANSI code)
Sub-section is protected also based on Directional Logic Selectivity, meaning that either direction pointing to the fault or breaker open status or energy flow, is received to allow the relay to sent trip signal and trip circuit breakers in the whole sub-section.
The following relays communicate direction 67 for immediate tripping with no delay:

- Bus-coupler
- Bus-ties
- Feeder - for blocking horizontal logic with directional protection
If the fault occurs on bus-bar then the information of relay direction (forward or reverse) is communicated between relays and tripping is selected based on logic above. If the feeder relay is not blocking, then the tripping signal is sent to isolate the complete sub-section meaning that all breakers in the sub-section will trip: generator, all feeders, and bus-ties/bus-coupler.
However, time graded tripping of all sub-section must be allowed if the feeder relay fail to trip for any reason (hidden failure). In this case bus-tie breakers will trip within 600 ms. The time grading may seem long but it must allow for downstream selectivity of distribution feeder and back-up to hidden fault e.g. feeder breaker failed to trip. Generator breaker, according to class, is allowed to trip for up to 1 second. This is the last resort of back-up.

Directional protection 67 will immediately trip the sub-section based on following logic:

A. If all horizontal direction arrows from the measuring points (relays with CTs) are pointing to the bus-bar – see table below

B. If the breaker is open but arrow from the other side of the bus-bar (or sub-section) is pointing to that direction

C. If the breaker is not energized (I < 10% and V < 20%) but direction (arrow) from the other side of the bus-bar (or sub-section) is pointing to that sub-section

Action takes place according to the following table (example for Tie-Breakers):

<table>
<thead>
<tr>
<th>Protection Relay</th>
<th>Relay Fault Direction</th>
<th>Partner Relay Fault Direction</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaker Protection Relay 1</td>
<td>→</td>
<td>→</td>
<td>No action</td>
</tr>
<tr>
<td></td>
<td>→</td>
<td>←</td>
<td>Trip Breaker</td>
</tr>
<tr>
<td></td>
<td>←</td>
<td>←</td>
<td>No action</td>
</tr>
<tr>
<td></td>
<td>←</td>
<td>→</td>
<td>No action</td>
</tr>
<tr>
<td>Breaker Protection Relay 2</td>
<td>→</td>
<td>→</td>
<td>No action</td>
</tr>
<tr>
<td></td>
<td>←</td>
<td>←</td>
<td>No action</td>
</tr>
<tr>
<td></td>
<td>←</td>
<td>←</td>
<td>Trip Breaker</td>
</tr>
<tr>
<td></td>
<td>←</td>
<td>←</td>
<td>No action</td>
</tr>
</tbody>
</table>

Figure 3.2 - Directional protection 67 will communication between SIPROTC relays on IEC 61850
4. Protection against hidden failure

Thinking overall philosophy, all aspects of design are covered against hidden faults. Each system and sub-system must be design with adequate amount of redundant devices in order to assure safe and robust functionality of the system. However, if the design overlooks certain aspects or failures that may depend on particular settings which can be set wrong, then we must be able to consider hidden failure in the system.

Advanced protection scheme described in previous chapter was based on hidden failure concept. There, differential protection is the main protection on most of the zones, except for the feeders where is optional, but directional serves as a back-up all over. Directional protection is thus set without any delay, no time grading. This is to assure complete redundancy. In previous chapter it is described that traditional time graded selectivity on bus-ties, bus-couplers and generators is selected in case that all above fails to operate. This has very low probability of occurrence, but nevertheless is implemented.

This chapter deals with number of methods available within the relay protection devices and used for the best possible protection against such hidden faults. The main focus in this chapter is on protection relay monitoring and breaker monitoring.

Monitoring of the generators and power management is covered by Generator Performance Controller (GPC) and coordination between relays and AVR. This is described in separate chapter.

4.1. Protection relay monitoring

Switch-On-To-Fault (SOTF) – hidden failures for e.g. ground switch and synch-check

Switch-on-to-fault (SOTF) is a protection function intended to trip a breaker when closed on to a faulted line or device. The high-speed over-current protection function is provided to disconnect immediately and without delay feeders that are switched onto a high-current fault. It serves for example to act as rapid protection:

- For connecting a feeder to a short circuit, typical grounding switch.
- For connecting non-synchronized bus-ties and is regarded as a back-up to a number of synch-check devices which are a back-up to the main synchronizer on bus-ties and generators.

The SOTF function can be programmed to protect the system only if the breaker was opened prior the short circuit current detection. In such case, if the breaker is closed prior the high current is detected, the SOTF function will not trip the breaker and thus will allow for the system coordinated tripping, as settings in the Relay Selectivity Plan.

**SF6 Gas Pressure Supervision**

Protection and supervision is done by a pressure switch installed on the SF6 gas chamber; there is also indication in front of the switchboard giving a red or green indication of the gas pressure. When the pressure is to low it will give a closed contact to the protection relay and a red indication in front of the switchboard. If the CB is initially open when gas pressure is to low, you will not get a “CB ready for operation”, and not be able to close breaker.

**Broken Wire Monitoring**

During steady-state operation the broken wire monitoring detects interruptions in the secondary circuit of the current transformers. In addition to the hazard potential caused by high voltages in the secondary circuit, this kind of interruption causes differential currents to the differential protection, such as those evoked by faults in the protected object. The broken wire monitoring function monitors the local phase currents of all three phases and the results of the broken wire monitoring supplied by the devices on the other ends of the protected object. At each sampling moment, the function checks whether there is a jump in one of the three phase currents; if there is, it generates the „suspected wire break” signal. There is a suspected local wire break if a jump has been detected in the affected phase and the current has dropped to 0 A.

**Fast Asymmetrical Measuring Voltage Failure "Fuse Failure Monitor".**

In the event of a measured voltage failure due to a short circuit fault or a broken conductor in the voltage transformer secondary circuit certain measuring loops may mistakenly see a voltage of zero. Simultaneously existing load currents may then cause a spurious pickup. If fuses are used instead of a voltage transformer miniature circuit breaker (VT MCB) with connected auxiliary contacts, then the „Fuse Failure Monitor” can detect problems in the voltage transformer secondary circuit. VT miniature circuit breaker and the „Fuse Failure Monitor” can be used at the same time.

A 3-phase failure of the secondary measured voltages can be distinguished from an actual system fault by the fact that the currents have no significant change in the event of a failure in the secondary measured voltage. For this reason, the current values are routed to a buffer so that the difference between present and stored current values can be analyzed to recognize the magnitude of the current differential (current differential criterion).

**Current Symmetry**

During normal system operation the currents are assumed to be largely symmetrical. The symmetry is monitored in the device by magnitude comparison. The smallest phase current is compared to the largest phase current. Asymmetry is recognized if:

$$\frac{|I_{\text{min}}|}{|I_{\text{max}}|} < \text{BAL FACTOR I as long as } I_{\text{max}} > \text{BALANCE I LIMIT}$$

Imax is the highest, Imin the lowest of the three phase currents. The symmetry factor BAL FACTOR I represents the allowable asymmetry of the phase currents while the limit value BALANCE I LIMIT is the lower limit of the operating range of this monitoring. The dropout ratio is about 97%.
Voltage Symmetry
During normal system operation the voltages are assumed to be largely symmetrical. The symmetry is monitored in the device by magnitude comparison. The smallest phase voltage is compared to the largest. Asymmetry is recognized if:

\[ |U_{\text{min}}| / |U_{\text{max}}| < \text{BAL. FACTOR } U \quad \text{as long as } |U_{\text{max}}| > \text{BALANCE U-LIMIT} \]

Thereby Umax is the largest of the three phase-to-phase voltages and Umin the smallest. The symmetry factor BAL. FACTOR U represents the allowable asymmetry of the voltages while the limit value BALANCE U-LIMIT is the lower limit of the operating range of this monitoring. The resetting ratio is about 97%.

After a settable time, this malfunction is signaled as „Fail U balance“.

Measured Value Acquisition Currents
Up to four input currents are measured by the protection devices. If the three phase currents and the earth current from the current transformer star point or a separated earth current transformer of the line to be protected are connected to the device, their digitized sum must be zero. Faults in the current circuit are recognized if:

\[ I_F = |I_{L1} + I_{L2} + I_{L3} + k_I \cdot I_E| > \Sigma I \text{ THRESHOLD} + \Sigma I \text{ FACTOR } \Sigma |I| \]

Factor kl \(14/\text{Iph CT})\) takes into account a possible different ratio of a separate IE transformer (e.g. cable core balance current transformer). \(\Sigma I \text{ THRESHOLD}\) and \(\Sigma I \text{ FACTOR}\) are the setting parameters.

The component \(\Sigma I \text{ FACTOR } \Sigma |I|\) takes into account permissible current proportional ratio errors of the input transformers which are particularly prevalent during large fault currents. \(\Sigma |I|\) is the sum of all currents:

\[ \Sigma |I| = |I_{L1}| + |I_{L2}| + |I_{L3}| + |k_I \cdot I_E| \]

As soon as a summation current fault is detected after or before a system disturbance, the differential protection is blocked. This malfunction is signaled as „Failure \(\Sigma I\)“. In order to avoid a blocking due to transformation errors (saturation) in case of high fault currents, this monitoring function is not effective during a system fault.

Current sum monitoring can operate properly only when the ground current of the protected line is fed to the fourth current measuring input (I4) of the relay. The I4 transformer must have been configured with parameter \(I4 \text{ transformer}\).

Measured Value Acquisition Voltages
Four measuring inputs are available in the voltage path: three for phase-to-earth voltages and one input for the displacement voltage (e-n voltage of open delta winding) or a busbar voltage. If the displacement voltage is connected to the device, the sum of the three digitized phase voltages must equal three times the zero sequence voltage. Errors in the voltage transformer circuits are detected when

\[ U_F = |U_{L1} + U_{L2} + U_{L3} + k_U \cdot U_{EN}| > 25 \text{ V} \]

The factor \(k_U\) allows for a difference of the transformation ratio between the displacement voltage input and the phase voltage inputs.

This malfunction is signaled as „Fail \(\Sigma U \text{ Ph-E}\)“. Voltage sum monitoring is only effective if an external displacement voltage is connected to the displacement voltage measuring input.

Voltage sum monitoring can operate properly only if the adaptation factor \(U_{\text{ph}} / U_{\text{delta}}\) has been correctly configured.

4.2. Breaker monitoring

Trip Circuit Supervision
As the Siprotec bay controllers are using most of the binary inputs for external interfaces, trip circuit supervision relays type has been introduced. Each 11kV circuit breaker has two shunt coils with independent trip circuits. Each of the two trip circuits has trip circuit supervision. Trip circuit failure will initiate alarm to operator and locally in the switchboard.
Circuit Breaker Failure Protection
The circuit breaker failure protection provides rapid back-up fault clearance in the event that the circuit breaker fails to respond to a trip command from a protection function of the local circuit breaker.

Whenever a short-circuit protection relay of an incomer/feeder issues a trip command to the circuit breaker, this is repeated to the circuit breaker failure protection. A timer in the circuit breaker failure protection is started. The timer runs as long as a trip command is present and current continues to flow through the circuit breaker poles.

Normally, the circuit breaker will open and interrupt the fault current. The current monitoring stage quickly resets (typical 10 ms) and stops the timer.

If the trip command is not carried out (circuit breaker failure case), current continues to flow and the timer runs to its set limit. The circuit breaker failure protection then issues a command (via the IEC 61850 communication) to trip the backup circuit breakers and interrupts the fault current.
The reset time of the feeder protection is not relevant because the circuit breaker failure protection itself recognizes the interruption of the current. For protection functions where the tripping criterion is not dependent on current, current flow is not a reliable criterion for proper operation of the circuit breaker. In such cases, the circuit breaker position will be derived from the auxiliary contacts of the circuit breaker. Therefore, instead of monitoring the current, the position of the auxiliary contacts is monitored. For this purpose, the outputs from the auxiliary contacts must be fed to binary inputs on the relay.

The figure below demonstrates the level of details to be accounted when calculating tripping times in e.g. for the relay selectivity. In addition to breaker tripping time of 3 to 5 cycles, time to pick-up, reset and additional margins must be taken into account. This approach allows for realistic relay settings for the relay time grading i.e. relay coordination.

![Diagram](image)

**Monitoring the Circuit Breaker Auxiliary Contacts**

It is the central function control of the device that informs the circuit breaker failure protection on the position of the circuit breaker. The evaluation of the circuit breaker auxiliary contacts is carried out in the circuit breaker failure protection function only when the current flow monitoring has not picked up. Once the current flow criterion has picked up during the trip signal from the feeder protection, the circuit breaker is assumed to be open as soon as the current disappears, even if the associated auxiliary contact does not (yet) indicate that the circuit breaker has opened. This gives preference to the more reliable current criterion and avoids over-functioning due to a defect e.g. in the auxiliary contact mechanism or circuit.

It is possible to disable the auxiliary contact criterion. The position of the auxiliary contacts is then not evaluated even if the auxiliary contacts are connected to the device.

**Common Phase Initiation**

Common phase initiation is used, for example, in systems with only 3-pole tripping, for transformer feeders, or if the busbar protection trips. If the circuit breaker failure protection is intended to be initiated by further external protection devices, it is recommended, for security reasons, to connect two binary inputs to the device. Besides the trip command of the external protection to the binary input, it is recommended to connect also the general device pickup to binary input.

Nevertheless, it is possible to initiate the circuit breaker failure protection in single-channel mode should a separate release criterion not be available.

If the current criterion is not fulfilled for any of the phases, the position of the circuit breaker auxiliary contact can be queried.
Current Flow Monitoring

Each of the phase currents and an additional plausibility current (see below) are filtered by numerical filter algorithms so that only the fundamental component is used for further evaluation. Special features recognize the instant of current interruption. In case of sinusoidal currents the current interruption is detected after approximately 10 ms. With a-periodic DC current components in the fault current and/or in the current transformer secondary circuit after interruption (e.g. current transformers with linearized core), or saturation of the current transformers caused by the DC component in the fault current, it can take one AC cycle before the interruption of the primary current is reliably detected.

The currents are monitored and compared with the set limit value. Besides the three phase currents, two further current thresholds are provided in order to allow a plausibility check. If configured correspondingly, a separate threshold value can be used for this plausibility check. The earth current IE (3·I₀) is preferably used as plausibility current. The earth current from the star point of the current transformer set will be used if it is connected to the device. If this current is not available, the device will calculate it from the phase currents using this formula:

\[ 3·I₀ = I₁ + I₂ + I₃ \]

Additionally, the value calculated by the protection relay of three times the negative sequence current 3·I₂ is used for plausibility check. This is calculated according to the equation:

\[ 3·I₂ = I₁ + a²I₂ + aI₃ \]

where

\[ a = e^{j120°}. \]

These plausibility currents do not have any direct influence on the basic functionality of the circuit breaker failure protection but they allow a plausibility check in that at least two current thresholds must have been exceeded before any of the circuit breaker failure delay times can be started, thus providing high security against false operation.

In case of high-resistance earth faults it may occur that the earth current exceeds the sensitively parameterized threshold value, the phase current involved in the short-circuit, however does not exceed the threshold value. The plausibility monitoring would prevent the breaker failure protection from being initiated. In this case the pickup threshold of the phase current monitoring can be switched over to the threshold value. A binary input can be linked to an external signal which indicates a high resistance fault, e.g. earth fault detection, or detection of displacement.
voltage. With this method, the more sensitively parameterized earth current threshold is also used for the phase current monitoring.

5. Soft start of system to avoid start-up inrush

Several factors are important when seeking a solution for fast start-up of diesel generators after a blackout:

- Lube oil temperature
- Cooling water temperature
- Load step requirements

Therefore the lube oil and cooling water heating need to be in operation for machines which shall be ready to operate.

The system start-up is done with two methods developed in details within R&D period:

1. **Fast black start**: In the black start mode the bus-tie and bus-coupler breakers are opened and there is a dead bus condition. Prior starting of the engine, the generator breaker is closed, including transformer breakers that did not trip. When the engine reach a defined speed and fires, the AVR ramps up the voltage, therefore ensure magnetizing of the transformers without any inrush current (no closure of breaker on zero cross voltage and saturation). Synchronization takes place via the tie-breakers and bus-coupler breakers. All breakers are equipped with Synchronization and synch-check devices.

2. **Fast pre-magnetization before transformer reconnection**: When a transformer has been taken out for service reconnection shall be done without the generator soft start. Pre-magnetizing of transformer after service takes place via a pre-mag control panel and is finished with 2-3 seconds. Feeder breakers are equipped with synch-check functionality in order to avoid any non-synchronous closure and inrush current. Special studies have been made to estimate the impact of magnetization when transformers of similar but vector groups are used and what is the adequate phase angle for limited inrush.

5.1.1. **Fast Black-start - fast start-up of essential consumers (E.g. thruster VSDs)**

When CBs have been opened due to under-voltage, they do not have to be manually reset before they can be re-closed. The HV transformer feeder CBs and the LV circuit breakers remain in the same position as prior to the blackout.

If a blackout should occur, the power cell (1/6 of the power plant) is segregated / isolated with the following start-up sequence:

1. PMS will initiate the black-out restart when the following permissive are given from the switchboard:
   - DEAD BUS signal (Closed contact on dead bus)
   - Generator CB open
   - Bus coupler CB open
   - Cable tie CB open
   - Generator 3-position breaker (-Q1) not in ground position
   - Bus-bar not grounded

2. PMS will send close command to generator CB

3. PMS receives Generator CB closed feedback status from the switchboard
4. PMS send generator start command to the DGCP
5. The engine will start and the DGCP sends signal “Engine speed above 90%” to Switchboard
6. The Switchboard will send EXITATION ON signal to AVR. The AVR will ramp up the voltage and “soft starts” the generator and all connected transformers and bus bars.
7. When 90% of nominal voltage has been achieved, the individual motors are started automatically based on “last running condition” or by re-start from PMS/IAS.
8. The pre-charge of the Thruster drive DC bus is initiated by the drive itself. (This is based on the 90% voltage at the secondary of the thruster transformer.
9. When the Thruster drive DC voltage has reached 85% of nominal voltage the drive is ready to start and closes the incoming breakers.
10. Drive is now ready for DP.

The estimated time to achieve automatic start is < 20 seconds, depending on the diesel engine start-up time.

If the voltage ramp-up should fail (voltage on generator below 90% for more than approx 20 sec) the switchboard will stop the engine, de-excite the generator and send EXCITATION FAILURE alarm to PMS.

**Soft Start Voltage Buildup by AVR**
AVR has a soft start feature with a user-adjustable setting to govern the rate at which the generator voltage is allowed to build up. This removes the generator voltage drop and also any potential voltage overshoot form nominal operating voltage during start-up of the system and completely removes any inrush due to transformer saturation for downstream consumers.

![Graph showing soft start voltage buildup](image)

AVR soft start capability provides for an orderly buildup of terminal voltage from residual to the voltage set point in the desired time with minimal overshoot. When the system is in startup, the voltage reference is adjusted by the amount calculated based on two parameters. These parameters are level and time. Soft start bias level is adjustable from 0 to 90 percent of the active mode set point in increments of 1 percent with a default setting of 5 percent. Soft start time is adjustable from 1 to 7,200 seconds in increments of 1 second with a default setting of 5 seconds. Figure illustrates a plot of the voltage reference showing soft-start bias at 30%, soft-start time at 8 seconds and a voltage set point of 100%.

**5.1.2. Pre magnetizing circuit for soft start-up of transformer**

The main task of pre-magnetization circuit of power transformers is to reduce the inrush current during start-up of the transformer. If a transformer is disconnected e.g. out for the maintenance, it shall be energized using the pre-magnetization system.
In this solution, this is accomplished by use of resistors connected at the transformer secondary at required voltage, i.e. 690V. Resistors in the circuit serve to damp any inrush oscillations but they introduce the increased impedance of the circuit and consequent voltage drop at the transformer primary. This results in voltage under 11kV during transformer energization from primary Breaker.

With voltage drop, the voltage phase difference is also introduced. Voltage drop and phase difference are larger with larger resistor. However, larger resistor provides lower inrush during closing the contactor at the pre-magnetizing circuit.

The voltage drop and voltage phase difference after the main Circuit Breaker at transformer primary may be so high that may create additional inrush during closing the main Breaker. This would be undesirable effect and would completely diminish the efforts to keep the inrush low at all times. The reasons for keeping the inrush low are following:

- Increasing the lifetime of transformers and downstream equipment due to avoiding high energy surges;
- Keeping protection relay settings sensitive to faults and capable to interrupt and isolate the faults with higher precision and speed.

Especially for closed ring power systems where all components will be affected, voltage and current transients should be limited to a minimum.

A 3-split closed ring power system with 3 off pre-magnetization control panels is shown below. However, the same pre-magnetization principles can be utilized for other power plant configurations.

**Start up algorithm**

Pre-magnetization sequence and closing of the CB are controlled by the transformer protection-relay (Siprotec) located in the LV compartment of the MV switchboard, see figure below.

The principle is that few seconds before closing a CB feeding a MV transformer, another power source is being connected to the secondary side of the transformer to Pre-magnetize the transformer core before closure of the CB. Immediately after the CB has been closed, the pre-magnetize source will be disconnected. The Pre-magnetizing of a transformer typically takes less than 2 sec.

As the Pre-magnetizing circuit may be connected form other sub-systems on the vessel, there is a possibility that these system operate at different voltage, voltage phase or frequency. In such a case, we defined the window in which closing CB is allowed for the safe transformer start-up with minimum inrush. If any faults are detected during the Pre-mag sequence/period, the Pre-mag sequence will be aborted, and an alarm will be sent to PMS.

Conditions to be fulfilled by the pre-magnetization circuit are following:

A) The voltage dip at the LV bus at the moment of closing the pre-mag contactor shall be less than the class rules.

B) The fuses used on both sides of the pre-magnetization circuit shall withstand the pre-magnetization current.

C) All elements in the pre-magnetization circuit shall not be destroyed by a the let-through current–time period of the fuse(s) (Contactor, resistor and cable).

D) The voltage deviation over the MV circuit breaker shall be less than certain magnitude and phase before closing the circuit breaker.

E) As soon as the MV circuit breaker is closed the LV pre-mag contactor shall open.

F) The pre-mag resistor shall in addition to the time/over-current relay be also protected by a temperature relay.
Figure 5.1 - Pre-Magnetization Block Diagram for one power section
6. Fault ride through capability

6.1. Fault ride through capability of generators

Generator data
Generator data reflect the dynamic study, fault ride through and relay selectivity. Therefore, generator data must be carefully examined and compared for DP3 closed ring systems. The traditional approach selecting generator for power rating and power factor is no longer sufficient. Generator data sheets, decrement curve, capability curve and number of other factors including AVR design must be adequately analyzed and supported for the dynamic study.

Gen-set torque
The table below is extract from generator data sheet. It shows that the gen-set can withstand up to 7 p.u. torque due to 3-phase short circuit on the grid and 9.29 p.u. for 2-phase fault. As can be seen in the remaining chapters, during faults the shaft torque is usually under 2 to 4 p.u. and under the limit of 7.14 p.u. If using GPC module EFORT (Enhanced fault ride through of the generator) the stress at the generator, i.e. power, currents, voltage and torque can all be significantly reduced.
General fault consequences for marine generators

During the fault, all generators will absorb extra energy accumulated from slower response of diesel engine. Therefore, speed on individual generator will increase during the fault and will oscillate after the fault is cleared. This will happen on all generator connected at the same bus where the fault occurred.

This situation is not so similar to the one defined for the large onshore power systems, where only single generator has to absorb all the accumulated energy during the fault; the rest of the system can be simplified and represented with infinite bus system, which has large (infinite) inertia and large short-circuit level. Usually, between individual generator and large power system are long transmission lines with relatively large impedance. This all contributes to stability issues of onland power generation.

On isolated systems, such as on typical marine vessel, the energy is always shared between the gen-sets, before, and after the fault. This reduces the out-of-step risk and provides damping of the oscillations of the machines. This can be clearly seen from the simulations and confirmed by the trials.

After the fault is cleared, active and reactive powers will always swing in the opposite phases, thereby providing very fast and efficient damping of the oscillations and regaining the system stability. This is due to relative inertia and power contribution from generators is significantly lower on isolated weak power grids, even if stability of single generator is compared to other 5 generators in the system. As the voltage increases the generators will be pulled-in back to synchronism by large forces created by synchronous pull-in torque – this can generate very large oscillations in power and torque on the shaft of each gen-set. These large deviations on the shaft will depend on numerous factors, but among the most important are speed of voltage recovery after the fault, which is directly influenced by the excitation system design and control.

Figures below show comparison between theory for Infinite bus and isolated grid, showing that same analogy is not applicable.
Example: Load angle for fault cleared in 100ms on infinite bus

Example: Load angle for fault cleared in 200ms on infinite bus

Figure 6.1 - Load angle for isolated marine systems – not relevant for the generator stability as all voltage phasors rotate during the fault and there is no voltage reference as is the case for the infinite bus systems

The main difference between the fault-ride-through cases and the synchronisation of the generator is that the voltage at the moment of re-connecting the system for the fault-ride-through is relatively low and is equal on all generators. This creates the soft-volt ramp-up effect after the fault and additional damping effect due to the weak grid and thus reduces the consequences for the generator stability in general. However, this does not diminish potentially dangerous forces at the shaft and current and voltage in the system after the fault.

**Syncronisation of generators**

The situation is more dangerous when synchronizing generators, due to the fact that both gen- sets (or systems) are running on full voltage (about 11 kV). During fault situation, the voltage drops equally on all generators.

The shaft torque may become much higher during synchronization than for the fault ride through, therefore remedies must be ensured in order to avoid connection of generators under non- synchronous conditions. The main limiting factor is voltage phase angle which must remain in general under 10 deg difference between the bus-ties before the CB is closed. Voltage magnitudes and frequencies may deviate within 5% as per droop curves but again it may not be good if large deviations exist on all parameters: phase angle, voltage, frequency. More voltage and frequency deviate, less difference in phase angle should be. Therefore, for bus-ties that connected passively, i.e. without active synchronizers and thus voltage and frequency magnitude can follow the droop curve, but the phase angle should be the lowest possible allowed. Speed of change in Hz is usually limited to only 0,1 Hz/sec, so this may be a problem if design does not
consider an active synchronization i.e. fuel change on governor to align the voltage phase angles through control of the frequency.

Due to above mentioned issues, system synchronization should be checked for each specific project.

**Voltage dynamics during load through-off and short-circuit fault**

The voltage will abruptly increase if several large loads are suddenly disconnected from the power grid due to e.g. false trip. The goal of studies was to check if the temporal over-voltage may be higher than the class rules, i.e. 120% nominal. The relay plan must reflect these voltage dynamics and thus prevent possible blackout due to spurious relay tripping due to over-voltage.

During load through-off on the engines, the negative (reverse) power can be relatively high on low loaded gen-set, but only for a short time, i.e. approx. less than 1 second is simulated in the model but this depends on the engine responses. The negative power relay is usually set to trip if negative power is high for longer than 5 seconds which makes system safe against false tripping.

![Diagram of a) 2 gen equally loaded and b) 2 gen with asymmetric load sharing](image-url)
Figure 6.2 - Generator (system) fault ride through: 2 gen online – bolted short circuit fault at transformer feeder cable in 5 sec., cleared in 5.5 sec.
Direct online induction motor model is representing as a group of loads (pumps, auxiliary loads, compressors, cranes, etc.) connected at the distribution transformer feeder. It is assumed that all operate with maximum load and torque.

During the short circuit, direct online (DOL) induction motor will loss the speed depending on its inertia and mechanical load torque. The load torque is selected to have point at 100% load when motor reach 100% speed. The inertia is selected typical for the larger pump.

It can be noticed that within 500 ms time (the worst case for most of the faults) the speed drops for about 50% (slip increases) which results in increased current inrush and electric torque after the fault is cleared.

However, motor is establishing its operation without problems. In fact, it has been seen that motor load inrush after the fault is beneficial for compensating the reactive power in the system and reduction of voltage over-voltage.

![Figure 6.2](image)

**Figure. 6.2 – Direct online motor (DOL) fault ride through: 2 gen online – bolted short circuit fault at transformer feeder cable in 5 sec., cleared in 5.5 sec**

### 6.2. Fault ride through capability of VSDs

One can notice that without kinetic buffering, see Figure 0-1 the DC voltage will drop to faulty level < 80% after 100 ms. The load torque \( T_m \) will drop from 60% down to about 20% within the measuring period of 1000 ms (1 sec.). The motor flux also drops to zero within 1 second.

The speed will drop from 60% down to 40% and will continue to drop very close to zero within next 3 seconds of time. These observations, especially for the propeller-motor speed confirm the realistic figures and expected results of the real drive.

With kinetic buffering we can see that more energy will be extracted from the motor while the speed is decreasing and utilized for feeding the drive and motor losses. This will have a consequence of reducing the voltage drop on DC link. Theoretically, this may be possible as long there is enough energy to be supplied from the rotating asynchronous motor (principle of wind turbine) run by the motor-propeller inertial effects, and this energy may be enough for up to a several seconds.

In fact, in Figure 0-2 with optimized controller gains, we are able to extract maximum available energy that can keep the thruster running after power supply cut-off for the next 2000 ms (2 seconds) of time. One can notice \( V_{dc} \) link > 640 Volt, and load torque \( T_m \) drop from 60% down to 10%.
One should be aware that these findings are only valid for high speed situation, i.e., >50% nominal speed. However, in the moment of fault on the main grid (11 kV) the thruster drive may be run on fixed pitch propeller with speed of less than 20% nominal. In such case, there may be much more limited power supplied from the rotating inertia and thus that drive would eventually trip on low voltage on DC bus.

Figure 0-1 VSD thruster measurements for DC_min_volt controller for kinetic buffering is OFF: motor stator current on phase A, thruster motor speed, electric motor torque $T_e$ and DC link voltage, flux

Figure 0-2 VSD thruster measurements for DC_min_volt controller for kinetic buffering is ON: motor stator current on phase A, thruster motor speed, electric motor torque $T_e$ and DC link voltage, flux
7. Synchronisation between Main MV Switchboard

7.1. Synchronisation of bus-tie breakers

The synchronisation of bus-tie breakers in the Main MV Switchboard must be given special attention to avoid un-synchronous power systems to be connected and thereby a possibility for total black-out. The operational sequences on to connect the tie breakers are described in document 51CX-00989.01.200-F-002.

The bus-ties will have a Master and Slave Breaker. The Slave breaker will close first and synchronisation will be taken care of by the Master breaker.

The permissive to close the Master breaker is based on the conditions that breaker is ready, interlocking is not blocking, slave breaker is closed and following external condition:

- Protection relay (7SJ64) synch check OK
- Synchroniser ready (Woodward SPM-D Healthy)
- Synch check relays (Deif CSQ and Woodward SPM-D) OK
- Synch check relay (Deif CSQ) ready (Healthy)

If all the above permissive OK then the breaker will close on signal from the synchronizer (Woodward SPM-D). The typical wiring of the synch check signals is shown in figure below.

![Figure 7.1 - Synch check for bus-tie breaker and bus coupler](image)

At the moment of synch-check is permissive to close CB between bus A and bus B the following conditions are recorded:

The oscillations in power, torque, voltage and current are high and recommended to be avoided.
- Voltage difference between buses = 1%
- Speed (frequency) difference between buses = 4% = 2.4 Hz
- Voltage phase angle difference = 30 deg.

- Voltage difference between buses = 1%
- Speed (frequency) difference between buses = 4% = 2.4 Hz
- Voltage phase angle difference ≈ 3 deg.

Figure 7.2 – Comparison of synch check window sensitivity: Active (Pe) and reactive (Qe) power, mechanical diesel power (Pm) and shaft torque difference responsible for shaft torsional structural loading on gen-sets
8. Generator Performance Controller

Excitation faults are usually covered within AVR and additionally with relays. Among number of faults that may occur (s-c at diodes, open diode, etc.) these are the typical excitation faults:

- Generator/AVR loss of voltage sensing
- Generator loss of field

Similarly, diesel engine faults are:

- Engine over-producing (full throttle, fuel rack blocked or loss of speed sensing)
- Engine under-producing (loss of fuel, water in the fuel, fuel blocked, etc.)

The diagnosis software within engine control system and AVR can typically diagnose number of such faults and beyond, related to particular faults within the machine such as: exhaust temperature high - due to fault with the fuel-air system of diesel engine, etc. and e.g. loss of voltage sensing diagnose due to fault in the voltage transducer at the AVR, or loss of field due to e.g. cable disconnected between gen and AVR.

There are number of faults that can not be detected by above mentioned algorithms. The power management and relay protection will usually aim to disconnect the faulty generator based on relatively simple logic and severity of the fault for the system e.g. with PMS. Such functions must always be coordinated with PMS, relays, AVR and engine control system.

Generator Performance Controller – GPC hereby is proposed to be used instead or as a main controller for faults that are not detected by above mentioned algorithms. GPC is connected to the generator measuring system only, and therefore does not depend on grid information contained within the PMS. In essence, GPC is using only the current and voltage measurement at individual generator and is able to detect number of system faults, thereby able to find the faulty generator and avoid risk of tripping the healthy one. This and such functionality in the past was only implemented within the PMS.

GPC should is able to detect failure modes not included above, where the gen-set is operating within alarm settings limits within relay devices, these failure modes are in genera as follows:

- Generator over-excitation (low, not so extreme as loss of voltage signal)
- Generator under-excitation (low, not extreme)
- Engine over-producing (low, not extreme)
- Engine under-producing (low, not extreme)

This chapter describes the main overview and give example of some faults relevant for the design of GPC. It also describes benefits when using GPC for dynamically positioned vessels, especially DP3 closed ring solution. The benefits are related to enhanced fault ride through capabilities of the generator and detection of generator faults in overall power system.

The GPC scope and supply has to split into several levels or modules:

1. **GPC Module EFORT**: Enhanced Fault Ride Through (EFORT) – improves generator responses during short-circuit faults (large and extreme faults);

2. **GPC Module FADER**: Generator Fault Detection and Response (FADER) – improves detection of faults on generators, and power system, performs as an advanced version of Power Management;
   a. Diagnosis module for generators in DROOP
   b. Diagnosis module for generators in ISOC mode
3. **GPC Module COMMAND:**
   a. Command: “Start all engines” (start all available engines)
   b. Command: “Start next in sequence engine(s)” (start only one or two engines)
   c. Command: “Isolate bus sub-section” (open bus-tie and bus-coupler)
   d. Command: “Isolate bus section” (open bus-tie from SWBD)
   e. Command: “Split the system” (open bus-tie or bus-coupler)
   f. Command: “Disconnect the gen-set from the grid”

GPC can give number of alarms and also can trip and de-excite the generator. The selected command must depend on the severity of the fault and situation with connected generators. For such functionality it is obvious advantage to at least have information on breaker status in the system, but this may not be absolutely necessary. Algorithms for detection of number of generators online available only from measuring the current and voltage at the generator incomer may suffice. Such algorithms have been already check in complex dynamic simulations, but are not yet implemented.

8.1. **GPC Levels and Network Topologies**

**GPC Level 0**

Topology 0 is minimum needed for GPC Level 0. Then only IO lost similar to shown below is available.

- PLC with necessary interface to collect internal signals and interface with PMS system.
- Alarms and monitoring necessary for basic level functionality.

The most basic GPC level involves only communication to higher level Power Management system.

Alarms are provided to PMS.

Commands are received from PMS.

Siemens is using Profibus DP communication protocol to receive and send data from Siemens PLC (GPC).

**GPC Level 1**

- This level includes monitoring and extended protection of the generators (FADER - G) and interfaces with the AVR related to voltage overshoot protection (Module EFORT).

To be able to use module FADER we need Network Analyzer. Topology 1 is minimum requirement.

- Extended alarms and monitoring necessary for extended level functionality (Level 1 includes level 0). Coordination with PMS related to preventive measures for fault detection generators.
- This level includes monitoring and extended protection of the generators (FADER - G) and interfaces with the AVR related to voltage overshoot protection (Module EFORT).
- Extended alarms and monitoring necessary for extended level functionality (Level 1 includes level 0). Coordination with PMS related to preventive measures for fault detection generators.

The topology is shown below. In the topology below, the information is circulated through IEC 61850. However, the main data is supplied to GPC from Network Analyzer (SIMEAS P) through Profibus DP.

The speed of transmission needed is relatively high, preferably higher than 100 ms refreshment rate.
**GPC Level 2**

- This level includes monitoring of the diesel engine and generators (FADER – G&D) and interfaces with the AVR related to voltage overshoot protection (Module EFORT).

**To be able to use module FADER we need Network Analyzer. Topology 1 is minimum requirement.**

- Extended alarms and monitoring necessary for extended level functionality. Coordination with PMS related to preventive measures for fault detection of gen-sets.
- Level 2 includes level 1 and level 0.

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**Figure 8.1 – Generator Performance Controller (GPC) – overview of modules**
9. OPEX cost breakdown comparison between DP3 closed ring and traditional operating modes

In addition to improving power system integrity to faults, when compared to existing class notations, there may be large number of additional benefits related to costs and maintenance for dynamically positioned vessels.

The benefits described hereby are mainly related to operating costs - OPEX of the vessel. The intention is to highlight the operational advantages that may justify the added investment costs, payable in relatively short time.

Main advantages for OPEX savings are:

- Reductions in total fuel consumption per year of operations;
- Reductions in total exhaust gas emissions per year of operations;
- Reductions in total running hours and thus obvious decrease in maintenance costs of the engines;
- Reduced engine running hours on low load – lower soot accumulation inside the engine and consequent maintenance costs related to this;
- Higher stand-by redundancy – more engines available for stand-by, reduction of risk that e.g. engine shall not be able to start – difficult to express quantitatively;
- Higher operational flexibility – possibility to have one engine-room with no running engines resulting in better HSSE conditions. Moreover, the main switchboard can still be live i.e. thrusters are available during the engine maintenance.

Weather – Met-ocean data

In the reality, the consumed power will depend on number of factors, e.g. wind/wave direction and relative heading of the vessel, sea current, water depth, thrust allocation algorithm used, and other factors. To find the correlation between the wind speed and power, the DP plots can be used.

In order to simplify the calculations, we may assume that heading control will be good to always position vessel towards the main wind/wave direction. This obviously makes easier to extract the wind data without consideration of the wind direction.

Diagram in Figure 9.1 is probability density function for Brasil Campos. There, data are sorted in the ascending order (from lowest to highest wind speed) and normalized from 0...100% of hours in the year (100% = 8760 hours).

Probability charts

The ordinate shows the PROBABILITY or expected results based on historical data. One interesting point can be read from the history diagram:

- In 2010, the vessel was operating under 90% of the time under half (50%) of the maximum wind speed
- In 2010, the vessel was operating 50% of the time under 11,5 knots, which is 11,5/38 = under 29% of the maximum wind speed recorded per year
As can be seen from DP capability plots, the vessel is designed to operate in failure mode where 2 thrusters are off-line (1 section is disconnected) and still capable to operate under 39…40 knots weather conditions.

The wind speed can be directly related to wave height, as shown from diagram from DnV in the next section.

Figure 9-1a. Probability density based on time history data of wind speed recorded at Brasil Campos (PETROBRAS SPECS)

Figure 9-1b. Probability distribution based on time history data of wind speed recorded at Brasil Campos (PETROBRAS SPECS)

Figure 9-2. Direct correlation between wind speed and wave height – indicating sea state conditions depend mainly on wind speed
Figure 9.3 - Diesel engine fuel consumption curves, with efficiency of generators accounted in Total BSFC

Operational modes compared in the OPEX cost calculations:

**Case A – Minimum 2 online (example) – DP3 closed ring mode**
- 2 engines online, closed ring situation and bus-tie/coupler breakers all closed

**Case B – Minimum 3 online (example)**
- 3 engines online, 1 engine in each engine room, closed ring situation and bus-tie/coupler breakers all closed

**Case C – Open section bus-ties (example)**
- 1 to 2 engines online in each section (engine room), OPEN ring situation and bus-tie breakers are OPEN

**Case D – All 6 online (example)**
- All engines are running from 0 to full load with closed bus/ring or
- Running 1 engine isolated in each sub-section, where all bus-tie breakers and bus-couplers are OPEN

The results are presented in the tables below. One can notice significant fuel savings when operate vessel with closed breakers, i.e. DP3 closed ring. Having closed bus or also the main cable ring makes no much difference for fuel calculations, but have significant impact to load flow i.e. load distribution. For fuel calculations, we consider number of generators that can connect to single bus and share the load.

In **Dynpos - ER mode** engines can operate up to about 70% ore more when only 2 online. This is due to in this mode we shall have fast load reduction system able to reduce load on thrusters in case of loss of generator and thereby prevent the relay trip of healthy generator and total blackout.

**Dynpos - AUTRO mode**, engines are not allowed to accept more than 50% of load when only 2 online. The power management start tables are set in order to allow the single failure of the gen-set can not impose step load on the others to be higher than their individual full load. Therefore in Dynpos AUTRO with 3 gen-sets online we are allowed to operate to 66%, with 4 gen-set up to 75%, etc.
Minimum 3 gen online mode – refers to the mode in which minimum 1 gen-set is operating in each of the engine rooms, therefore overall minimum 3 gen-sets online in the closed ring configuration. There, engines can be loaded without important restrictions. In DynPos AUTRO, up to 66% and in ER class notation even more. Running engine higher than 75% does not provide any benefits in the fuel savings, therefore there is no point in loading engines high and risking that the speed of fast load reduction algorithm will not be able to react on time, due to high energy that rotating inertia of the gen-set has to supply.

Engine response to step load related to fuel costs

The trend of engine manufacturers is to reduce the weight of the engine. This contributes to better and faster engine responses and shorter acceleration on the compressed air during start-up and faster blackout recovery. However, it also reduces the inertia of the engine and negatively influence the fast load reduction, see the chart below.

Figure 9.4 – Time to under-frequency (-10%) when engine need to accept the load – assumed that the engine has fixed load and is not able to respond fast so that the frequency drop is only determined by the energy in the rotating inertia, expressed by inertial time constant H is seconds

Figure 9.5 – Fuel consumption in kg/hour for each configuration of the operating modes, and power consumed per time based on weather data and DP capability plots
## FUEL CONSUMPTION

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>HP</th>
<th>HP/year</th>
<th>HP/year</th>
<th>Savings per year</th>
<th>Savings per 20 years</th>
<th>Rate %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siemens</td>
<td>DP3 Closed Ring Main 2 online - Dynapos AUTO</td>
<td>3071</td>
<td>65584</td>
<td>65584</td>
<td>143</td>
<td>1493</td>
<td>180</td>
</tr>
<tr>
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<td>65584</td>
<td>65584</td>
<td>143</td>
<td>1493</td>
<td>180</td>
</tr>
<tr>
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</table>

## FUEL RATES AND SAVINGS

<table>
<thead>
<tr>
<th>Yearly rate</th>
<th>Rate day average</th>
<th>Savings</th>
<th>Savings per year</th>
<th>Savings per 20 years</th>
<th>Rate %</th>
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</thead>
<tbody>
<tr>
<td>Hrs/year</td>
<td></td>
<td></td>
<td>Hrs/year of Max model</td>
<td>HRS of Max model</td>
<td>% of max model</td>
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<tr>
<td>14356.9</td>
<td>40.08</td>
<td>574.75</td>
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<td>415,527.7</td>
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<td>574.75</td>
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</table>

## GENERAL MAINTENANCE COSTS

<table>
<thead>
<tr>
<th>Running hours Total</th>
<th>Running hours per engine</th>
<th>Number of engines</th>
<th>Hours between overhaul</th>
<th>Hours between overhaul</th>
<th>% of Max model</th>
<th>Engine-use</th>
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<tbody>
<tr>
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## RISK OF SOOT ACCUMULATION IN ENGINES

<table>
<thead>
<tr>
<th>Running hours under 30% load</th>
<th>Running hours under 30% load - 100% load of maximum</th>
<th>% of Max model</th>
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</thead>
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<tr>
<td>984</td>
<td>984</td>
<td>3.45 %</td>
</tr>
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<td>984</td>
<td>3.45 %</td>
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<tr>
<td>984</td>
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