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Enhanced Blackout Recovery Testing of DP Vessels

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Abstract

Total blackouts have occurred on vessels that operate either with a common power system configuration or with the power system split into two or more independent power systems. It is more prevalent in the former configuration. In the latter configuration, internal and external common cause failures are often the cause rather than individual equipment failures.

Not all causes of vessel blackout can be recovered from – i.e. there may be some scenarios where recovery will not succeed even if it operates correctly. Success depends on whether the common cause failure that initiated the blackout remains active.

Where recovery includes restart of generators, drives, major consumers and auxiliary services, the success of blackout recovery often depends on the absence of active lockout functions on the Main Switchboards, thruster drives restart time etc.

The primary aim of this paper is to:

- Review the various blackout recovery test procedures that are sometimes performed as part of annual trials and to evaluate their effectiveness in replicating a real blackout condition
- Present an additional test procedure that could be performed to improve the effectiveness of Blackout Recovery Testing
- Investigate the impact that any additional blackout recovery tests would have on equipment longevity
- Identify system components and methodologies that could be incorporated into existing and future designs to facilitate blackout recovery tests – **Build To Test.**

The additional test proposed herein is considered as an enhancement of the existing tests that may already be performed as part of blackout recovery testing. Furthermore, the tests are not aimed specifically at any particular equipment manufacturer as the tests aim to replicate failures that could be experienced on any vessel regardless of equipment manufacture and design. However, the implementation of the test circuit may vary depending on the equipment type.

Introduction

The common causes of a blackout are often a result of equipment or common system failures and in some cases due to operator error. However, the way in which a power system blacks out, can be broken down into two main groups:

a) Power system operating as a common system (bus-ties and transfer feeders / cable interconnectors closed)
b) Power system operating as multiple independent systems (bus-ties or transfer feeders / cable interconnectors open)

With a common power system configuration, any of the following causes could cause a complete power system blackout:

a) Failure to over voltage / excitation on one generator causing multiple generators to trip on over voltage protection or field failure protection.

b) Failure to over speed / over frequency on one generator causing multiple generators to trip on reverse power protection and the faulty generator tripping on over frequency protection or engine over speed.
c) A severe load sharing imbalance (kW or kVAr) caused by one generator taking the entire load then tripping on over current can cause other generators to trip on under frequency or under voltage as they support the additional sudden application of load
d) Low speed caused by common fuel contamination problem leading to tripping on under frequency.
e) Low engine speed caused by combustion air starvation
f) Tripping of multiple generators on overcurrent due to crash synchronisation or inadvertent connection of a stationary generator.
g) Tripping of multiple generators on reverse power or over frequency due to excessive regeneration from industrial load
h) Tripping of multiple generators on overload or low frequency due to overload in plant or lack of generating capacity.
i) Over speed due to ingestion of combustible gas.
j) Failure of a bus-tie or interconnector to open when 1st stage protection operates
k) Failure of common auxiliary systems such as fuel or cooling etc.

For a multiple split bus power system configuration, a total blackout is only likely to occur due to the following:

a) Lack of generating capacity in surviving plant when DP control system and industrial consumers transfer load to surviving power systems.
b) Low speed caused by common fuel contamination problem leading to tripping on under frequency.
c) Tripping of multiple generators on overload or low frequency due to overload in plant or lack of generating capacity
d) Tripping of multiple generators on overcurrent due to crash synchronisation when the single bus tie between two independent switchboards closes (out of sync).
e) Low engine speed caused by combustion air starvation
f) Over speed due to ingestion of combustible gas.
g) Although the primary power system is considered as two or more independent systems, an incorrect configuration of a particular auxiliary system could result in a total blackout.
h) Auto-changeover of systems from one power plant to another as a result of a blackout could transfer the fault to healthy system

What prevents a blackout recovery?

Knowledge and experience have shown that there are numerous conditions or system configurations that can prevent a successful recovery from blackout. These include, but are not limited to:

a) Protective functions on healthy generators, feeder circuits and propulsion / thruster equipment operating via their lockout protection relay thus preventing the equipment from being restored as part of the recovery sequence.
b) UPSs failing or locking out due to the brownout conditions that often prevail leading up to the blackout.
c) Circuit breakers at the low voltage and auxiliary system levels being selected to local control thus inhibited from closing as part of the blackout recovery sequence.

d) Failure of the propulsion / thruster drives to re-connect to the system due to their pre-magnetization supply being out of synchronism with the main switchboard.
e) Insufficient validation of the PMS blackout recovery sequence at the design / test phase.
f) Incorrect configuration of the auxiliary system preventing the main system from recovering.

Present Test Regimes

Blackout recovery testing as part of annual trials normally involves the configuration of the vessel power system such that a single generator supplies the power system with the remaining generators offline but available for starting and connection to the power system at the request of the vessel's Power Management System (PMS).

The disconnection of the last generator is usually initiated by tripping its circuit breaker either via the PMS workstation, the generator Emergency stop circuit or by tripping the generator locally at its respective incoming switchboard panel. Other tests include the controlled ramp down of generator (hence system) voltage or frequency to a value less than its protective trip level via the Automatic Voltage Regulator (AVR) or engine governor respectively.

Some of the aforementioned tests can be considered representative of a sequence of events that would lead to a blackout due to operator error and in the case of the voltage and frequency ramp tests; these can be considered consistent with a PMS output control relay error (e.g. a sticking or welded contact inside the relay enclosure).

Generally, the aforementioned tests are considered the industry accepted method of initiating a blackout for the blackout recovery test. However, these tests do not replicate or simulate a power system disturbance that could occur due to equipment failure or system failure that results in a power system blackout. As such performing this test in isolation may not fully evaluate the blackout recovery sequence or prove the operation of certain electrical protective functions do not lockout and prevent the recovery sequence operating as expected. It is not just the effect the disturbance will have on the main generating switchboard, but also the LV consumers which are fed via transformers from this switchboard that are critical for the restart of essential equipment e.g. fuel and lubricating pumps etc. Furthermore, these tests are generally performed as they are considered to be 'kind' to the power system and as such do not put the equipment such as switchgear under greater stress than during normal switching duties and limit the exposure of the connected equipment to any disturbance.

Figure 1 shows the controlled ramp-down of generator voltage to the under voltage trip level to create a blackout. In order to evaluate the performance of such a test, it is necessary to understand the effect the controlled reduction in voltage will have on the main components of the electrical power system (e.g. thruster drives, generators, etc.) prior to the blackout. During the controlled reduction in voltage, the connected thruster drives will experience a controlled reduction in DC link volts and motor output power will reduce accordingly. The thruster motor output voltage, will also reduce with a possible reduction in motor output power depending on its loading at the time of the test. LV consumer loads will reduce in output (resistive / induction load loads).

In the case of a controlled reduction in generator frequency, the generator AVR flux (v/Hz) limiter may become active resulting in the generator terminal voltage being reduced proportionally to frequency and generally the power system will react in in a similar manner to that of it be being subjected to a controlled reduction in generator voltage.

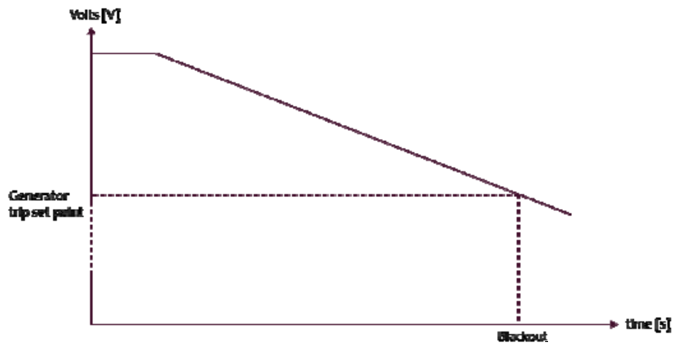


Figure 1 – Blackout Recovery Test – Controlled reduction in a generator terminal voltage

In the case of the other tests that are sometimes performed for blackout recovery, there is little evidence to suggest that the power system will be subjected to any appreciable transient conditions prior to the blackout as the tests are initiated by simply disconnecting the last on-line generator.

An additional Blackout Recovery Test Method

It is evident that blackout recovery tests should be wide ranging and should as far as possible simulate system transients that can occur prior to and during the blackout in a controlled manner to verify the ability of the healthy systems to recover following a blackout. Tests should also verify the integrity of the various vessel electrical protection systems to ensure that they operate correctly during a fault, whilst allowing healthy systems to recover post fault as part of the recovery sequence. The tests should confirm that essential auxiliary systems necessary for the recovery of the power plant system are not affected by any transient prior to the blackout and as such do not prevent the blackout recovery sequence from being initiated or successfully completed. The tests should also confirm that the principle electrical components of the power system (thruster and propulsion drives, switchboards, UPSs etc.) are sufficiently robust and can tolerate without damage system outages and the subsequent reconnection.

This paper has identified that blackouts will often be preceded by a transient condition (voltage, frequency or a combination of the two). Therefore, a test is proposed to simulate or replicate these conditions as accurately as possible. These conditions are summarized below:

a) Transient voltage variation – a sudden drop (or rise) in voltage due to a close up fault, an AVR or excitation fault, the loss of an on-line generator or the loss of a sizeable reactive load causing an excessive voltage rise.
b) Transient frequency variation – a sudden drop (or rise) in frequency due to a close up fault, an engine governor or fuelling fault, the loss of an on-line generator or the connection (or loss) of a sizeable active (resistive) load.
c) In the case of system short circuits, and depending on the type and location of the fault there will be sudden dip in system voltage (the fault current is predominantly reactive power), which results in a reduction in active power demand which is seen almost like a load rejection on prime movers (i.e. frequency increases transiently). As system voltage recovers (excitation system reacts in an attempt to restore volts) or the fault is cleared (protection operates to isolate the faulty circuit) there will be corresponding load application seen by the prime movers (a drop in frequency).

Depending on the damping and the control of the system, this oscillation may occur for a short duration post fault. It is during this time all of the protective systems associated with the healthy switchboards must remain inoperative. However if they were to blackout, the healthy systems should be available to recover as part of the blackout recovery sequence.

For each test performed, the blackout recovery should evaluate the ability of essential systems including the propulsion / thruster drives to reconnect to the system (and available for DP control where applicable), paying particular interest to VFD pre-charge / pre-magnetization supplies which may be operating asynchronously from the main power system.

Figure 2 below illustrates the voltage and frequency excursions that can occur during short circuit conditions leading up to a power system blackout.

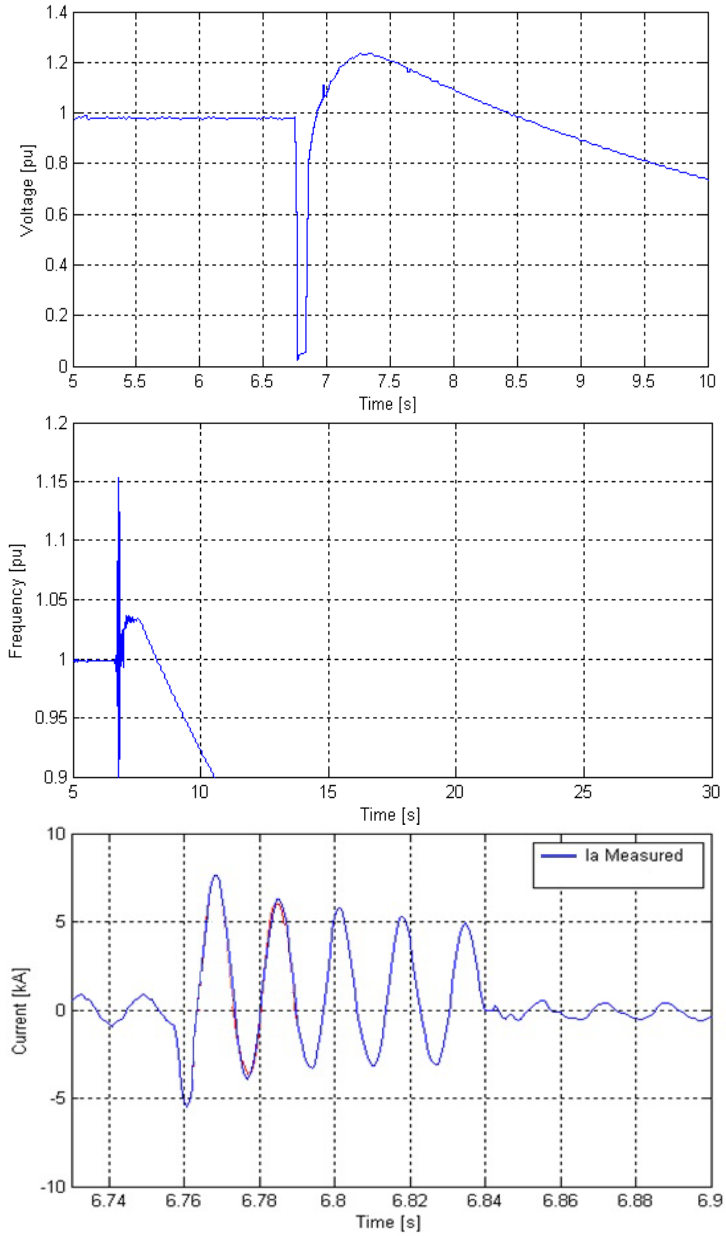


Figure 2 - Voltage, frequency and current disturbances during a fault

Excitation Interruption

An interruption to the excitation on a generator is a potential method of simulating voltage and frequency transients that could occur prior to a blackout and hence verifying the ability of the vessel's power system to successfully recover from any blackout that may occur as a result of either an equipment failure or a system fault. This test can be effective in two ways:

a) When applied to a generator that is single running on the main bus, the interruption is seen as a genuine power system outage

   By implementing a test, which does not solely rely on the tripping of the generator circuit breaker, the busbar will suffer a realistic collapse in volts and potentially a transient frequency increase due to a reduction in generator output power. The under voltage protection or other protective functions would operate in this instance to trip the generator circuit breaker and associated bus ties / interconnectors. The blackout recovery would commence thereafter. This test will potentially demonstrate that that the power plant, including its auxiliary systems are tolerant to the transient voltage and frequency variations experienced and as such can recover as part of the blackout recovery sequence.

b) When a generator is operating in parallel with another generator, the power system could be arranged so that the loss of excitation on one generator causes the generator to trip on under excitation and subsequently resulting in the remaining online generator tripping on overcurrent or other protective functions. It may be that the generator protective settings will need to be temporarily modified to achieve the desired generator trip scenario. However, with careful planning, this test could simulate a voltage depression and hence frequency variation on the power system prior to and subsequently after the first generator tripping. Again such a test will potentially demonstrate that that the power plant, including its auxiliary systems are tolerant to the transient voltage and frequency variations experienced and as such can recover as part of the blackout recovery sequence.

   Note:

   As with all brushless generators installed on vessels, the exciter field connects to the main generator winding via a set of rotating diodes. With this configuration, it is not possible to assist in the removal of the main field voltage due to the blocking effects of the rotating diodes. However, real-time site data shown in Figure 3 demonstrates that by interrupting the generator excitation on a brushless generator, the rate-of-change of generator output voltage that can be achieved is sufficient to replicate voltage (and hence frequency) excursions, which would occur prior to the blackout.

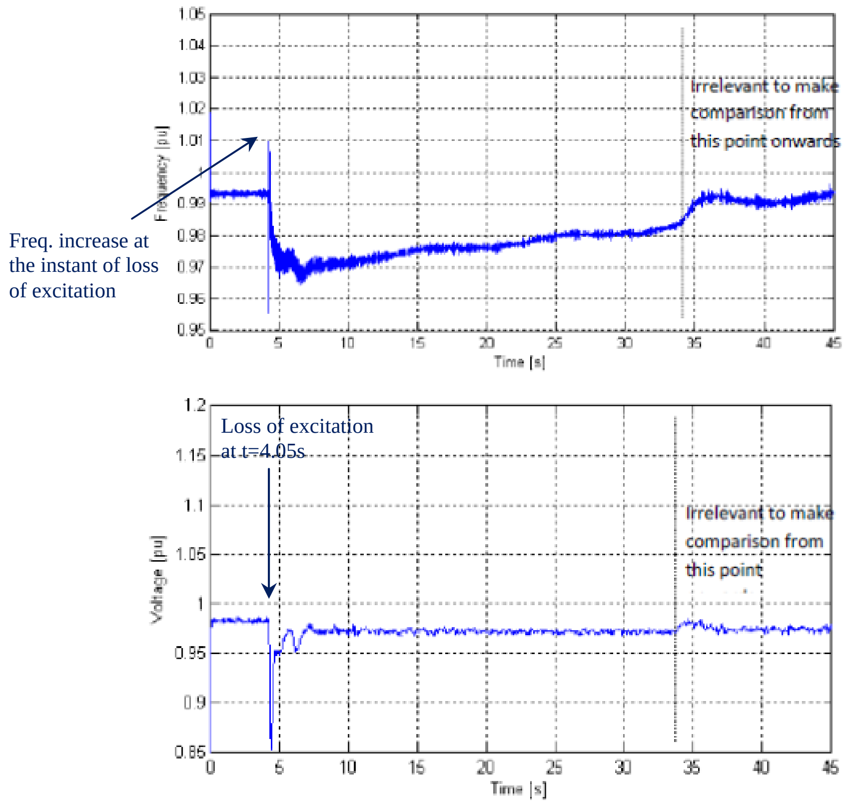


Figure 3 – Voltage and frequency during loss of excitation on one generator whilst operating in parallel

Test Implementation

It is recognized that the tests discussed in this paper should be performed in a controlled manner, with essential services fed from an islanded switchboard that will not be affected by the test. Once confidence has been established that a given test has been successful, a calculated decision should be made whether to repeat the test with the system configured in a more representative vessel configuration to further validate the blackout recovery.

Excitation Interruption

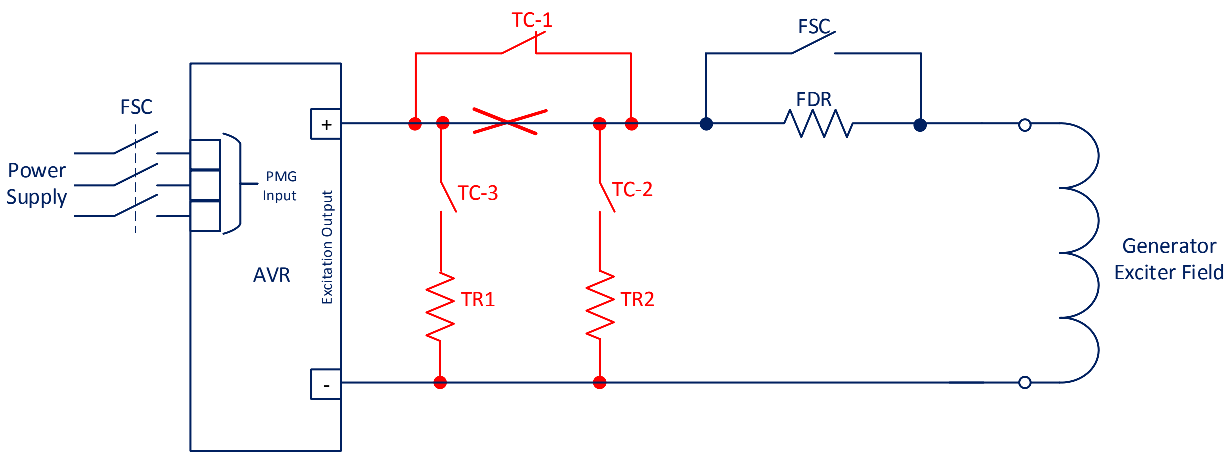
The excitation interruption test involves adapting the AVR excitation output circuit for one (or more) generator(s). This can be achieved in a number of ways depending on the AVR type and the control circuit. This will need to be checked on a case-by-case basis.

a) Operating the AVR in Automatic Mode and by simulating an excitation trip signal from the generator protection relay at the AVR panel. The simulated protection trip interrupts the generator PMG power supply to the AVR, interrupts the AVR output to the generator exciter and introduces the field discharge resistor in the generator exciter field circuit. The resistor provides a path for the generator exciter field current to be discharged whilst having the desirable effect of reducing

the L/R time constant of the exciter field, which in turn helps remove the stored energy from the exciter.
For the test to be effective i.e. to allow the voltage and hence frequency disturbance to occur for the duration permitted by the generator protection, it may be necessary to disable or disconnect the AVR protection alarms where installed (e.g. watchdog) to prevent an unwanted, instantaneous trip of the generator circuit breaker.

b) Operating the AVR in manual field current regulator (FCR) control and introducing a separate field discharge resistor to rapidly discharge the generator exciter field. An additional contactor or similar may be required to achieve this. This contactor will also allow for remote operation of the circuit.
When operating the AVR in manual control it will be first necessary to stabilize active and reactive power on the respective main busbar before switching the AVR from automatic to manual control.
For this test to be effective, it will be necessary to stabilize the vessel load as far as practically possible prior to selecting the generator AVR to manual control to ensure acceptable reactive power load sharing is maintained. However, the method of reactive (kVAr) load sharing implemented on the vessel would need to be evaluated before safely enabling manual control.

Figure 4 shows how a typical generator exciter field circuit can be modified implement the test circuit and Figure 5 shows how the test circuit could be implemented practically. In this case, the generator excitation system will be configured for manual excitation (FCR) control.



FSC = AVR Field Suppression Contactor

FDR = AVR Field Discharge Resistor

TC = Test contact from Test Box (3-pole relay)

TR1 = Test resistor (similar value to generator exciter field resistance)

TR2 = FDR for field suppression purposes

Figure 4 - Typical generator exciter field circuit modified to implement the test circuit

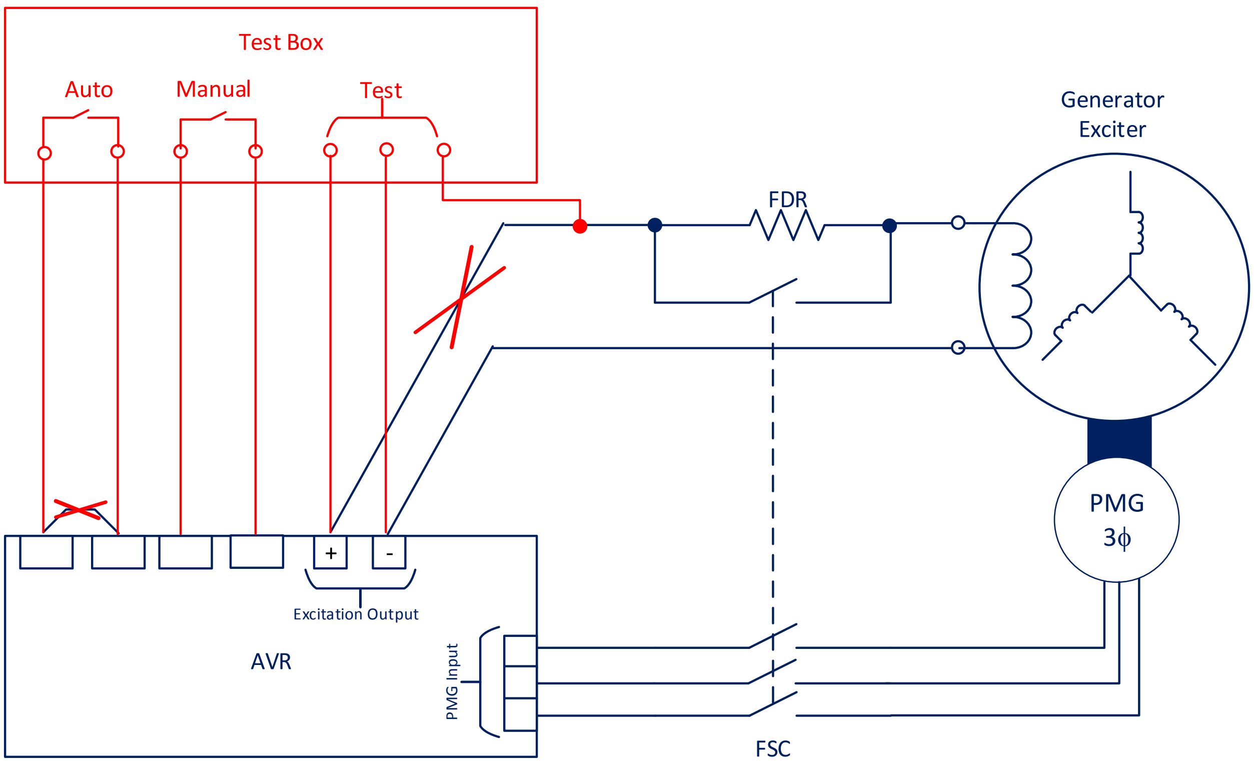


Figure 5 – Practical test circuit

Comparison of Test Methods

As mentioned previously, the authors consider the excitation interruption test as a potential additional test to the tests already performed in the evaluation of blackout recovery performance. The table below provides a comparison of the various test methods available including the excitation interruption test.

Function	**System / Equipment fault (Protection Trip)?**	**Operator Error?**	**PMS Fault?**
E-Stop Engine	x	√	x
CB Trip	x	√	√
Ramp Volts to trip Set-point	x	√	√
Ramp Hz to trip set-point	x	√	√
Excitation Interruption	√	x	x

Table 1 – Comparisons of Test Methods

Other Test Methodologies

The preceding test is one potential test method to replicate a transient disturbance prior to a blackout and the authors recognize that there are other potential methods worthy of investigation, such as the creation of a transient frequency excursion, sudden load application or loss of AVR voltage sensing. The test should try to minimize changes in any of the control and protection settings as far as possible.

Evaluation of Equipment Integrity during Blackout Recovery Testing

As mentioned previously, one of the objectives of these tests is to verify that the principle electrical components of the power system, such as thruster and propulsion drives, switchboards, UPSs etc. are sufficiently robust and can tolerate without damage (and if necessary self-protect) during system outages and can be brought back into service as part of the blackout recovery sequence without the need for operator intervention.

The following section summarizes the expected robustness of the thruster Variable Frequency Drives (VFD) in tolerating the voltage and frequency excursions that could be experienced during the aforementioned test.

a) Propulsion & Thruster Variable Frequency Drives

Type: Diode Front End (DFE)

With all DFE drives, the rectifier is uncontrolled and the magnitude of the DC link voltage will follow that of the input or supply voltage and as such will follow the voltage excursions that could be experienced prior to and during the blackout. The tests should demonstrate that there is no damage to the drive components during this condition.

Under Frequency: The drive will normally monitor the bus frequency whatever the method of control. If this falls below a pre-set level, a power reduction will be initiated by reducing the drive torque limit. This function is designed to act very quickly in the event of a generator tripping. The test should prove there will be no damage to the drive during this condition and that the drive VFD under-frequency spillover functionality operates correctly.

Over Voltage: It is important that the power system is tuned in such a manner that any transient overvoltage due to a load rejection does not exceed the overvoltage rating of the converter. If, however, excessive overvoltage arises as a result of the test, the drive will trip its respective feeder circuit breaker to avoid exposing the semiconductors to excessive voltages beyond their nominal rating. The test is therefore two-fold: 1) to demonstrate that the power system is tuned correctly and 2) no damage or unwanted tripping of the drive occurs.

Under Voltage: Depending on the drive manufacturer, The DC link may be supported for a period (depending on the speed of the motor) by the motor EMF via the drive kinetic support function. However, the DC link will eventually trip on undervoltage. Without this kinetic support, the DC link voltage of the converter will collapse as a result of the main system voltage drop and this will trip the converter and circuit breaker. The tests should verify that following an under voltage, the drive is not inhibited from restarting either as part of the blackout recovery sequence or following restoration of main supplies.

b) Uninterruptable Power Supplies (UPS)

The tests should verify that the transient variation of system voltage and frequency prior to the blackout does not cause the UPS to trip. The robustness of UPSs in terms of overvoltage and undervoltage (brown outs) needs to be discussed with the equipment supplier before performing any of the aforementioned tests.

Effects on equipment longevity due to Blackout Recovery Testing

There is a general concern that performing any form of blackout recovery test, either by simulation of a voltage and / or frequency transient condition prior to the blackout, the manual disconnection of on-line generators or by a controlled ramp-down of voltage or frequency to below the protection trip thresholds can impose stresses on the electrical plant. This is not just limited to the generators being disconnected but also the consumers that see a reduction in voltage and / or frequency (either rapidly or in a controlled manner) and as such may react to this excursion by either attempting to maintain operation (kinetic support in the case of conventional voltage sourced converter thruster drives). Some equipment may even to attempt to support the main network power supply e.g. Active Front End (AFE) Converter drives. Some loads will automatically shutdown to self-protect their power electronic circuits depending on the rate-of-change of voltage and / or frequency they are subjected to.

Consideration should also be given to consumers that are fed off the corresponding LV systems that will also blackout as part of the test. What is the impact on operational life of equipment that is disconnected and reconnected after a few seconds?

The method of invoking a blackout as described earlier in this paper involves the rapid reduction in system voltage to a level below the protection relay under voltage trip set-point and being held at this level for sufficient duration until the under voltage protection operates - resulting in a blackout. The intention of this test is to create a realistic disturbance on the power system that could occur prior to a real blackout situation.

As discussed previously a rapid reduction in system voltage will have a corresponding impact on system frequency due the reduction in active power seen by the connected generator(s). The interaction of system voltage and frequency variations may cause power swings between connected generators depending on the exact test configuration.

So what are the systems or items of equipment that could be affected by performing these tests and what impact will it have on equipment longevity?

a. Generators

The sudden reduction in excitation voltage will result in the exciter field energy being discharged through the test circuit discharge resistor. Due to the main field of the generator being fed via a rotating diode rectifier assembly, there will be no mechanism to rapidly discharge the main field. In this instance, the rotating diodes will be subjected to significant reverse voltages. Generally, the diodes are selected to have Repetitive Reverse Blocking Voltage of at least 200% of the maximum (peak) field voltage. On this basis, no damage or weakening of the rotating diode assemblies following these tests are envisaged.

A reduction in excitation current, may cause an increase in generator PMG voltage (due to regulation), but the PMG open circuit voltage will have been selected to be less than the maximum input voltage rating of the AVR (or manual field current regulator).

With any load rejection situation, the generator(s) will be subject to rotor acceleration (the braking effect of the load torque has been removed), but the load rejection seen by the generators in this instance would be less than the worst case (full load) rejection that could be experienced by the generators during actual operation.

b. Prime Movers

The sudden reduction of load will be managed by the engine fuel control system. In the case of common rail direct fuel injection engines, this is managed by the fuel injector control and should impose no significant stress on this system - the injectors will simply reduce to 0% duty cycle on load rejection due to the over-speed condition of the engine.

For hydraulically actuated governor control systems, there will be some stress applied to the actuator and fuel linkage, but based on the anticipated active power reduction (and active power application, in the case of a power swing being invoked) to each generator, this is envisaged as being significantly less than a full load rejection.

c. Circuit Breakers

Vacuum circuit breakers at medium voltage are designed to interrupt rated current and rated voltage without damage. Switching operations at rated conditions can be as high as 10,000 operations before the vacuum bottles need to be replaced. Due to the very low arc energy, the rapid movement of the arc root over the contact and to the fact that most of the metal vapor re-condenses on the contact, contact erosion is extremely small.

Therefore, no premature wear is envisaged to the vacuum circuit breakers by performing these tests.

It is recognized that load switching using vacuum as an insulating medium can cause high voltage spikes (up to 2 x rated voltage), but all equipment installed (including cables) will have insulation systems rated for this switching phenomena.

d. Variable Speed Drives

In the case of diode front end (DFE) variable frequency drives with kinetic support functionality, which are subjected to a rapid depression in network (input) voltage, the control logic within the drive will (if provided) automatically invoke the kinetic support function to maintain dc link volts. In the event of the network voltage failing to recover (i.e. in the event of a real blackout) or if there is insufficient kinetic energy in the thruster motor to support the DC link, the drive will pulse inhibit the output IGBTs and trip its incoming circuit breaker due to a prolonged DC link under voltage. The impact on the semiconductor operational life is negligible due to the controlled & coordinated manner of this protection functionality.

A reduction in system frequency, either rapidly or in a controlled ramp, will have negligible effect on the variable speed drives.

e. Ship Service Transformers

Transformers normally operate within the linear region of their magnetic saturation curve where the core magnetic permeability is high and the core magnetizing current is low. Energising a transformer that possesses residual flux in its core can push the core into saturation causing high currents to flow. These currents are known as inrush currents and are not considered as a fault condition. These currents, which are not too dissimilar in magnitude to short circuit currents, can impose large mechanical stresses on the transformer primary windings. Generally transformers are designed with sufficient bracing to counteract these mechanical forces and as such the repeated energization of transformers as part of the blackout recovery tests should have little effect on transformer longevity.

e. Summary

It is not expected that any premature wear will occur to main electrical power system components during the blackout recovery tests described within this paper. The transients imposed are significantly less than that would occur in the case of a full load rejection to a single generator. However, from a good practice perspective, it would be recommended that different generator combinations are used for each annual test to ensure that each generator and its associated protection equipment is configured and reacts the same as the initial test case.

Future System Design

In order to facilitate the testing and any subsequent re-validation, it can be considered beneficial to have systems designed that readily permit this testing. This could include, but not limited to, control systems embedded in the switchboard, in the VFD or in the PMS or in any combination of these that could simulate or replicate actual blackouts that occur on vessels. This could allow remote instigation of the fault (e.g. control room) without the need for operation’s personnel being present at the equipment.

It is recommended that discussion with equipment vendors take place to see how this could be implemented.

Conclusion

This paper has reviewed the various blackout tests presently performed as part of annual trials and has identified an additional test which involves the interruption of the excitation for connected generator(s) to simulate power system transients that could occur prior to a blackout. By performing such tests annually or twice annually, the efficiency of testing would also be improved which will have the desirable effect of reducing the overall testing time.

Due to the relatively benign nature of these excitation interruption test, this could be performed annually as part of the annual proving trials programme without affecting equipment life / longevity. These tests could also compliment any fault ride-through (short-circuit) testing requirements.

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