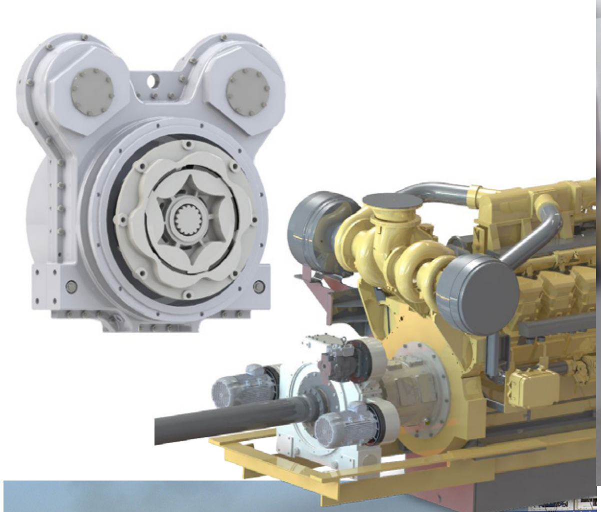
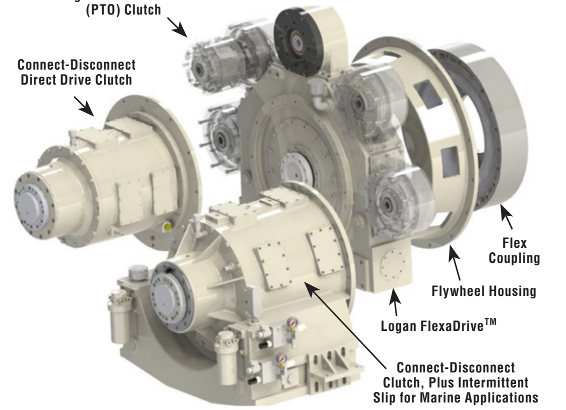
FlexaGen®
VARIABLE SPEED GENERATOR

Functional
DESCRIPTION



BREAKWATER GROUP

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manufacturers of clutches and brake products

canal

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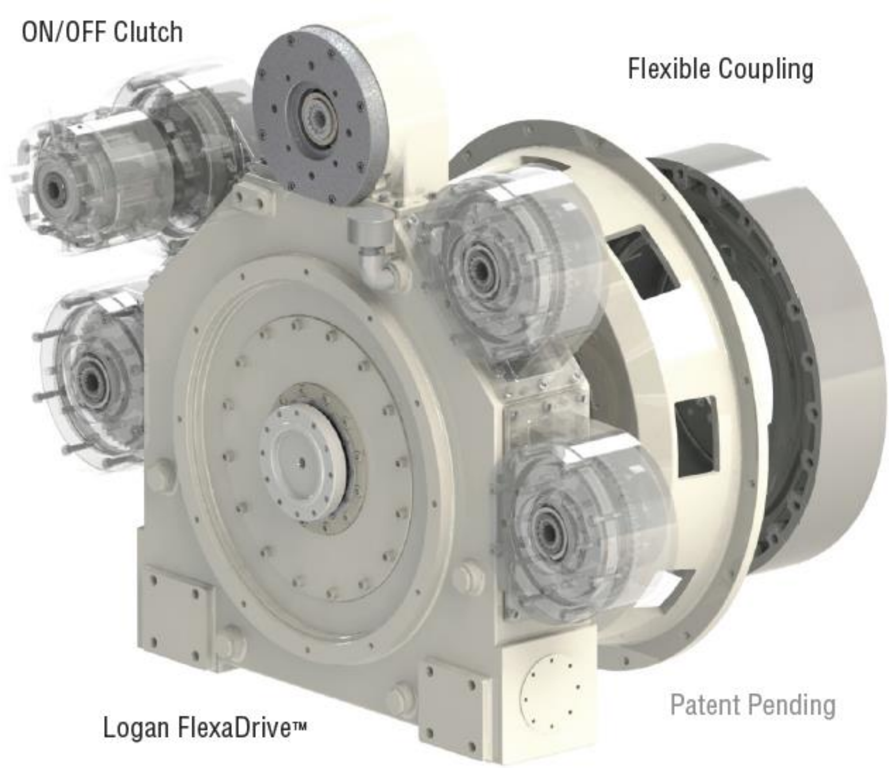
December 2016

Contents

Revision No.	Date	Details	Edited By
1	13th June 2016	First Release	Chris Wright (Canal)
2	21st Nov 2016	Added description of self-start module	Chris Wright (Canal)
3	9th Dec 2016	Added descriptions of double ended ferry application and front-of-engine application	Chris Wright (Canal)

In a typical application, the **Logan FlexaDrive** is sandwiched between an engine and transmission (or marine propulsion shaft); allowing up to ten live PTO pump pads for a wide range of hydraulic pump requirements, such as drive shafts, pumps, pulleys, and clutchable power take-offs. The pad positions can equally be used to attach a motor for power into the shaft (PTI) or for electrical power out, where the use of modern electronic power conversion technology allows the motor to be used as a generator.



The FlexaDrive system is described on Logan Clutch website:
http://loganclutch.com/FlexaDrive

The diagram below shows a FlexaDrive with all five tower positions populated. The unit can be supplied with any number of towers (between zero and five), and additional positions can easily be added at a later date. The gear ratio between the main shaft and each individual PTI/PTO position can be optimized according to the application.

Motor/Generators used with a FlexaDrive can be of several types, including induction and permanent magnet. In general the specific application will determined the choice.

The FlexaDrive can be paired with a clutch for many applications. However, the clutch is not an integral part of the system and some applications will not require it.

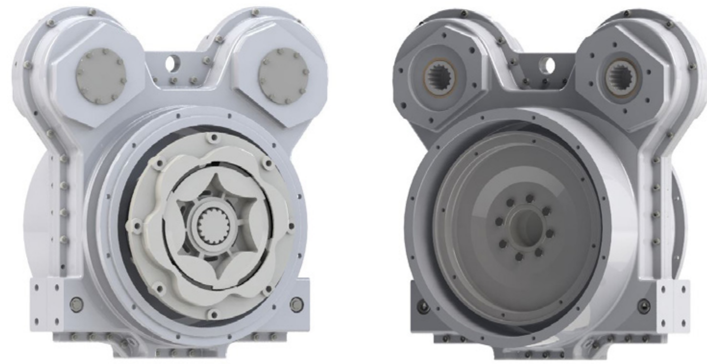
FlexaDrive Features:

- Up to ten live PTO/PTI positions
- Short axial length plus full torque transmission
- Available in SAE 1, 2, 3 as well as 0 and 00 Bell Housing sizes
- Flexible couplings in SAE 11.5", 14", 18" and 21" flywheel sizes
- Up to 3000 hp or 2237 kW @ 2600 RPM
- Short axial length plus full torque transmission

A smaller version of the FlexaDrive, with a shaft capacity of 730hp and two PTO/PTI towers is also available. The functional descriptions in this document are generally true for either version.

The FlexaGen is the electric power conversion system that allows connection of a motor/generator - typically positioned on a FlexaDrive PTI/PTO tower – to an AC bus. This power conversion package is bi directional in terms of power flow. It allows:

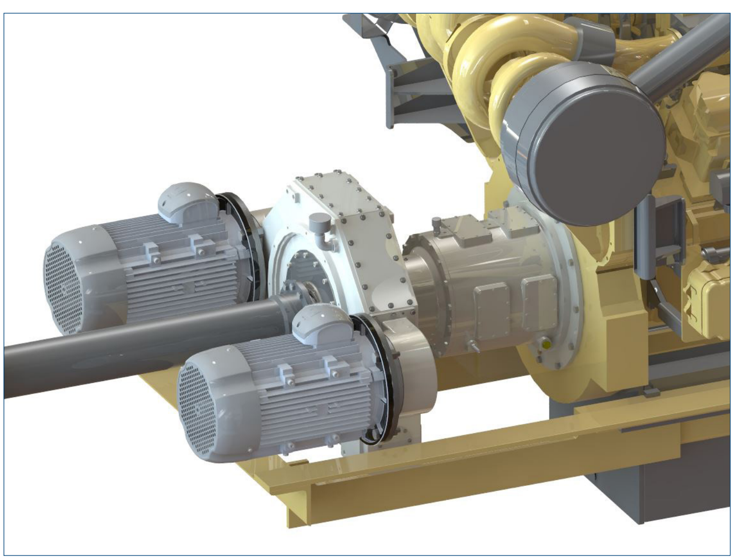
- The motor/generator to be utilized as a motor using the AC bus as a source of power
- The motor/generator to be utilized as a generator, using the main shaft as a source of power and supporting the AC bus (either alone or in parallel with other FlexaGens or Diesel Generators)



Note that the motor/generator is a typical VFD-rated unit, with no unusual requirements. Any induction or permanent magnet motor controlled by modern transistor-based drive technology can be used to apply positive torque to the shaft (motoring) or to apply negative torque to the shaft (braking). When braking, a motor becomes a generator with the direction of power flow being from the shaft to the AC bus. The Variable Frequency Drive (VFD) and Active Front End (AFE) stages of the FlexaGen allow us to control this in both directions.

For example, we can:

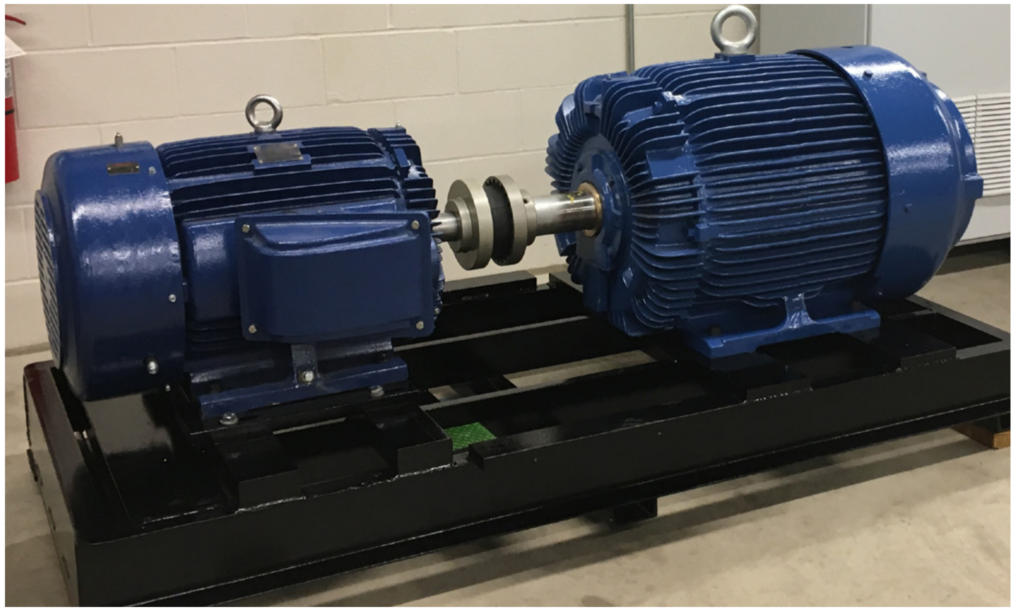
- Regulate the mechanical output of the motor when 'motoring'. This may involve using a speed reference to control the speed of the shaft or a torque reference to regulate the torque applied irrespective of speed. We are even able to apply a power reference, making the power drawn from the main AC bus by the FlexaGen a constant.
- Regulate the electrical output of the system when 'generating'. This may involve supporting the AC bus with a voltage and frequency reference.



Note that a FlexaGen is able to share the load in either direction. For example, two FlexaGens can be utilized to support two motors on the same shaft, with each making a proportional contribution to the work. Similarly, two parallel FlexaGen systems – whether associated with single or multiple shaft lines – can support a common AC plant. Load sharing techniques are discussed in more detail later in this document.

Typically, the FlexaGen can switch between these modes of operation (eg from motoring to generating or from following a speed reference to a torque reference) seamlessly within milliseconds.

The photograph below shows two FlexaGen cabinets under test.



The following is a list of Marine applications. This is not intended to be exhaustive. Indeed, new applications for the FlexaDrive/FlexaGen technology are being continually developed.

Support For Propulsion Auxiliaries

All auxiliaries required for complete operation of the thruster or propeller (including steering if this is a function of the thruster) should best be supported by the propulsion shaft (as opposed to electric power from vessel services). This is a more reliable and robust arrangement as the function relies on less input resources (eg a rotating shaft input and 24V dc control power can be the only two required inputs for self-sufficient, autonomous operation of the propulsion function). A function relying on less input resources for proper operation is statistically more robust.

This also removes risky common dependencies of multiple propulsion functions on a single resource (eg many props relying on a single AC service bus). If a single failure causes loss of the vessel service bus then multiple props can be affected.

The auxiliaries can be supported via the FlexaDrive (PTO supporting HPU for hydraulic auxiliaries, or PMG / FlexaGen for electric auxiliaries). Belt drives can be eliminated by connection of an HPU directly to the FlexaDrive PTO.

Low Level Motorized Propulsion via PTI

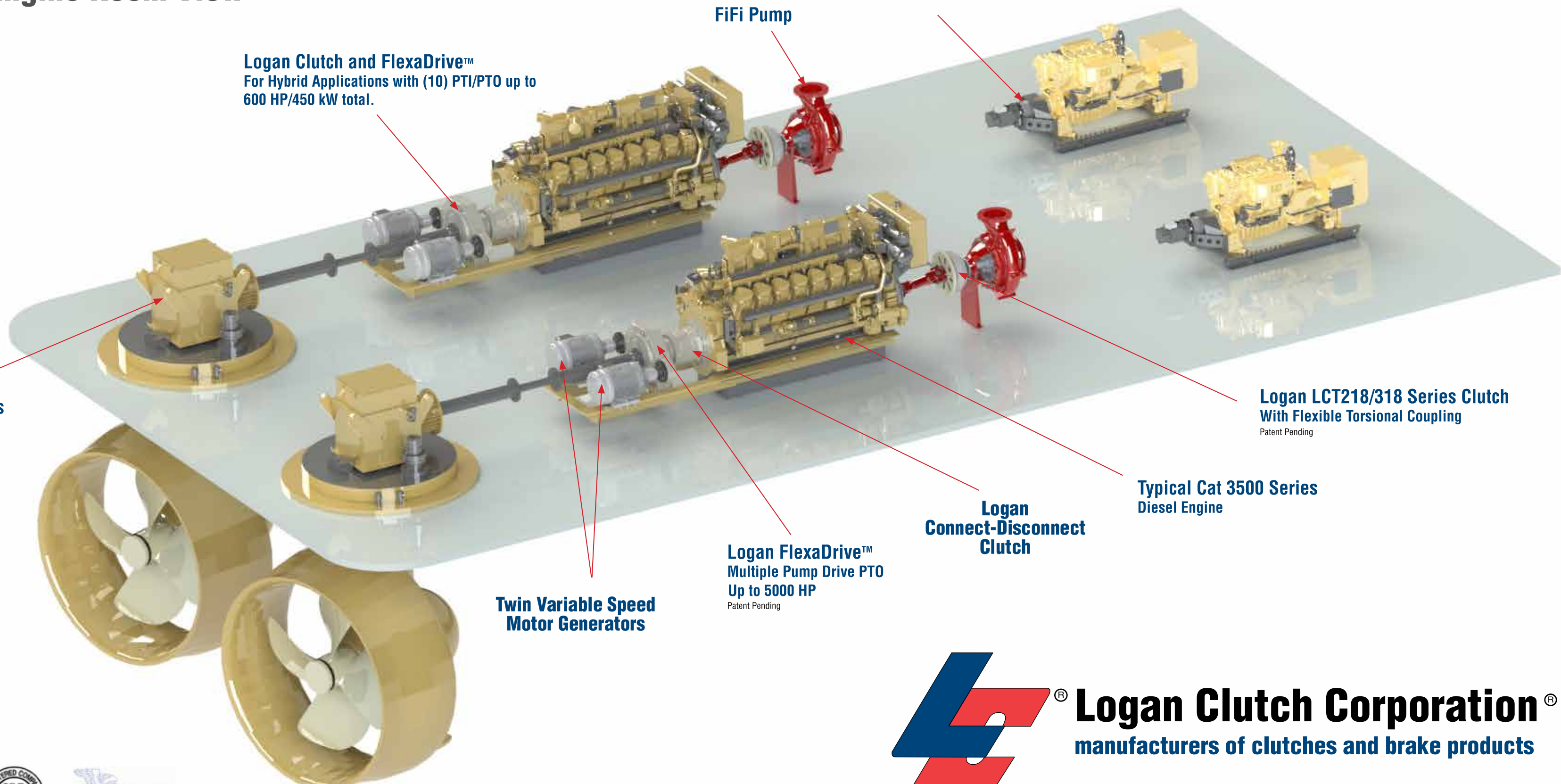
Where a large main engine supports a prop or thruster, the engine may be clutched out and shut down, especially when propulsion power requirements are low. This saves engine hours, reducing costs. It also makes low level operation of the large engine unnecessary, reducing emissions relative to output power and fuel consumption. Alternative use of a smaller, but optimally loaded, diesel generator is known to reduce fuel consumption and therefore CO_2 emissions. Notably other undesirable emissions, such as carbon monoxide, sulphur dioxide and particulates are reduced by even greater percentages through cleaner burning within the optimally loaded smaller engine.

A relatively small motor can drive the shaft through one of the FlexaDrive’s PTI/PTO positions using power originating at one or more auxiliary generators. The power produced from the motor can be sufficient for station keeping, low speed transit, or emergency ‘get-me-home’ functionality.

Note that multiple PTI/PTO positions can be utilized with multiple motors to increase the total power available. The FlexaGen system has load sharing functionality.

Logan Clutches for Main Propulsion, Auxiliary Power Take-Off Drives / PTO, and FiFi Applications

Typical Engine Room View



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Support of Undersized Main Engines via PTI

This application is a variant of that described immediately above.

In some cases a main engine may be deliberately undersized. There are obvious advantages in initial cost of machinery and further ongoing benefits in engine efficiency, economy, reduced emissions and maintenance. This is especially attractive if the vessel can operate for long periods below its maximum power requirement.

The FlexaDrive system, coupled with the FlexaGen, allows auxiliary generators to provide additional propulsion power to the shaft via one or more electric motors. In this mode of operation the motors provide a torque contribution to the shaft in support of the main engine.

Battery Powered Propulsion

For low power propulsion, and in cases where it is undesirable for diesel engines or generators to be running, electric propulsion can be supported by energy storage arrays (typically batteries). This is achieved by temporarily supporting the FlexaGen's dc-link from a battery array as an alternative to the ac-fed front end. The dc-link voltage may be regulated using a DCDC converter fed from the batteries. The ac plant may also be supported from the same source via the FlexaGen's active front end. At time of writing, we know of many existing examples of battery-supported propulsion that have been previously implemented (but without the advantages that the FlexaDrive offers):

- A harbor tugboat arriving on location - but before the client vessel is ready for assist - uses low level battery support of vessel systems and propulsion. This allows polluting diesels to be shut down while vessel service power and sufficient propulsion for station keeping is maintained.

- A vessel transiting a protected ecological zone is able to shut down diesel engines and reduce emissions to zero.

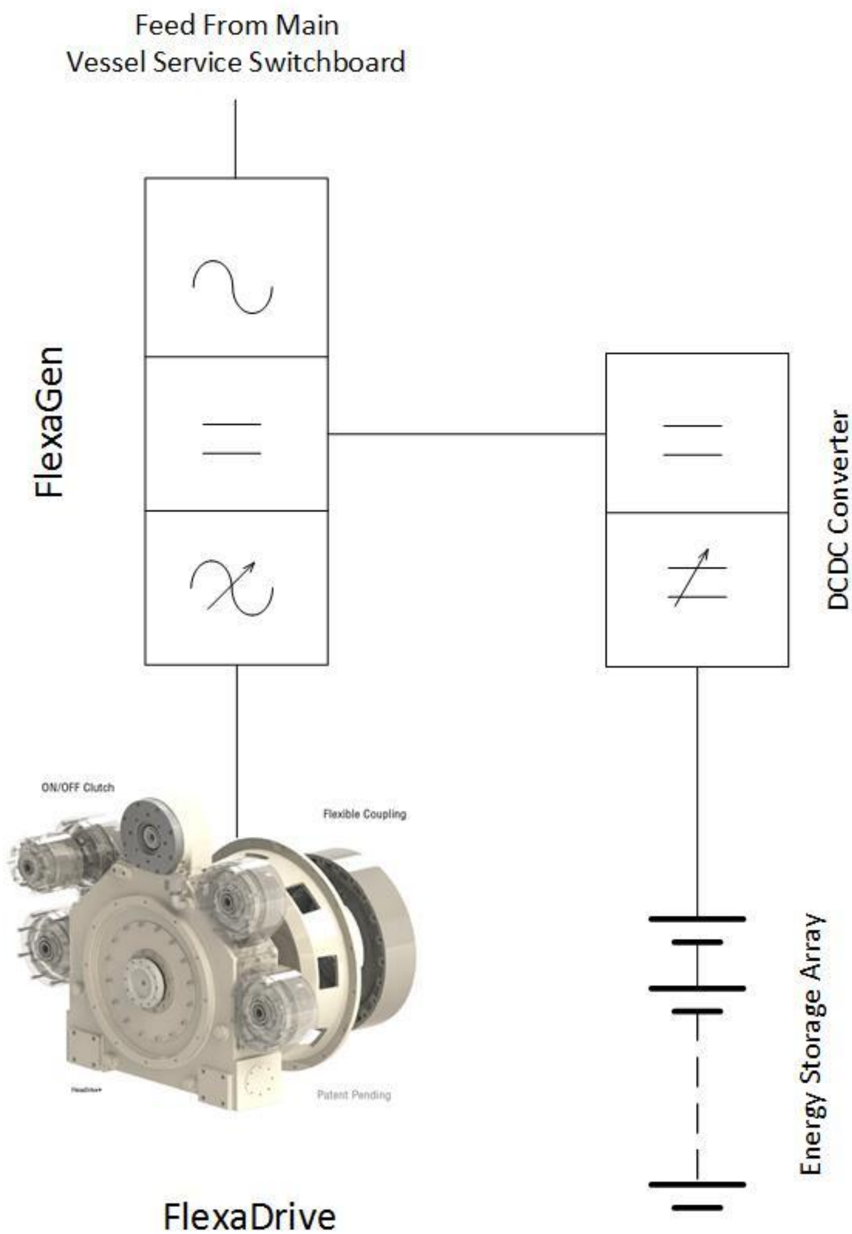
- A support vessel serving offshore oil and gas installations is able to shut down all diesels in the event of a blowout or other leakage of flammable gasses. This reduces the risk of the vessel acting as a source of ignition for the gasses. The vessel's essential systems are maintained from batteries along with low level propulsion allowing 'emergency egress' from the danger zone.

Variable Speed Generator

This technique utilizes a standard asynchronous induction motor or permanent magnet machine to act as a motor when required (see above) or as a shaft generator creating electrical power from the main engine and supporting vessel services. It utilizes modern power converter technology and creates an AC output at plant frequency (eg 50Hz or 60Hz) irrespective of the shaft rpm. The maximum available power developed by this ‘FlexaGen’ is dependent on shaft rpm, the motor/generator sizing and drive sizing. Ultimately there is a mechanical limit of 150kW (at 3000rpm) for each position on the FlexaDrive. Multiple positions can be used to increase the overall power.

The ‘FlexaGen’ can mimic the properties of a diesel generator and can be configured to run in parallel, sharing load proportionally according to its configuration settings. It can also support the AC bus independently up to its maximum power capability (limited by its own rating, the motor/generator size and the shaft rpm).

It can be used to mitigate the effects of large step loads on the bus, or to replace a diesel generator connected to the common bus (providing n+1 redundancy), or to make the running of diesel generators unnecessary while the main engine is running. It can also act as a ‘bus saver’ to maintain the bus in the event that other sources (eg diesel gens) fail.



Undersized Auxiliary Gens (or Oversized Loads)

In cases where a vessel is underpowered (in terms of its electrical plant) FlexaGens can be introduced to increase capacity. This is rarely the case for new-builds, but often additional equipment is added over the life of a vessel in service. In some cases this can lead to difficulty in ensuring that sufficient power can be provided to ensure n+1 redundancy of generators and enough online capacity to handle step loads or other disturbances. These issues arise quite frequently with existing vessels, especially where newer systems have been added or where the vessel has been repurposed. We have seen such issues being addressed by more aggressive load-shedding systems, but the addition of electronic variable speed generators can be a better solution. This is especially appropriate where the use of larger electrical loads tends to coincide with the main engines running.

Propulsion Support (where PTO mode is never needed) – "Lite" Version

In cases where the system is never required to function as a generator - only to provide motorized support for propulsion - it is possible to replace the Active Front End of the system (along with its LCL filter) with a simple rectifier front end. This alternative hardware reduces the cost of the system and can also reduce its physical size/footprint. Although it is no longer possible to develop electrical power from the main shaft, the system can still be used to drive the shaft – or to provide a torque contribution to the shaft in support of the main engine – up to its rated capacity.

An Alternative to Traditional Hybrid Power and Propulsion Systems

Marine Hybrid power and propulsion systems are relatively new. However several technologies have been introduced and successfully implemented over recent years. Typically an arrangement is used where a large main engine can drive the thruster or propeller through a clutch and a large motor. The clutch may be opened and the main engine shut down, leaving the motor to drive the propulsion shaft using electric power. A 'hybrid' between diesel-electric and direct-drive is achieved. However, the motor must be able to cope with the torque of the main engine, which is transferred directly through it. This can lead to the selection of oversized and expensive motors (and oversized variable frequency drives to support them).

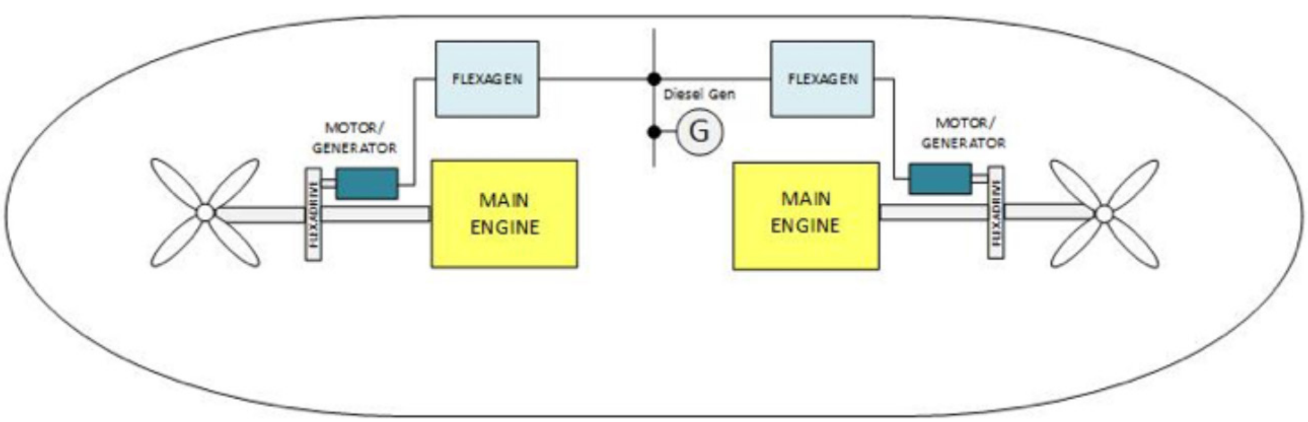
A FlexaDrive/FlexaGen system allows the use of appropriately sized motors and power converters to achieve the same benefits as the Hybrid power and propulsion systems currently on the market.

Double Ended Ferry

Double-ended ferries have interchangeable bows and sterns, allowing them to shuttle back and forth between two terminals without having to turn around.
A symmetrical FlexaDrive/FlexaGen arrangement allows power from both main engines to be transferred to either shaft, and for main engine power to be utilized to support the vessel service plant, load sharing with diesel generators or allowing them to be shut down entirely.
In this way, the main engines can be sized for optimum efficiency, reduced emissions during transits and greater redundancy.

Example:
For any crossing, it is most efficient to apply the majority of power to the aft prop. The aft main engine – rated at 500kW - applies 400kW and is supplemented by 200kW from its FlexaGen in PTI mode for a total power of 600kW to the prop. The 'fwd' main engine drives its FlexaGen (in PTO mode) consuming 400kW. Of this, 200kW is transferred to the aft shaft, and 200kW supports vessel services (with the diesel generator shut down).

In the scenario above, the aft shaft power is optimized for the crossing, and each main engine is 80% loaded for optimum efficiency and reduced emissions. When the crossing direction is reversed, the roles of the two FlexaGens are reversed.

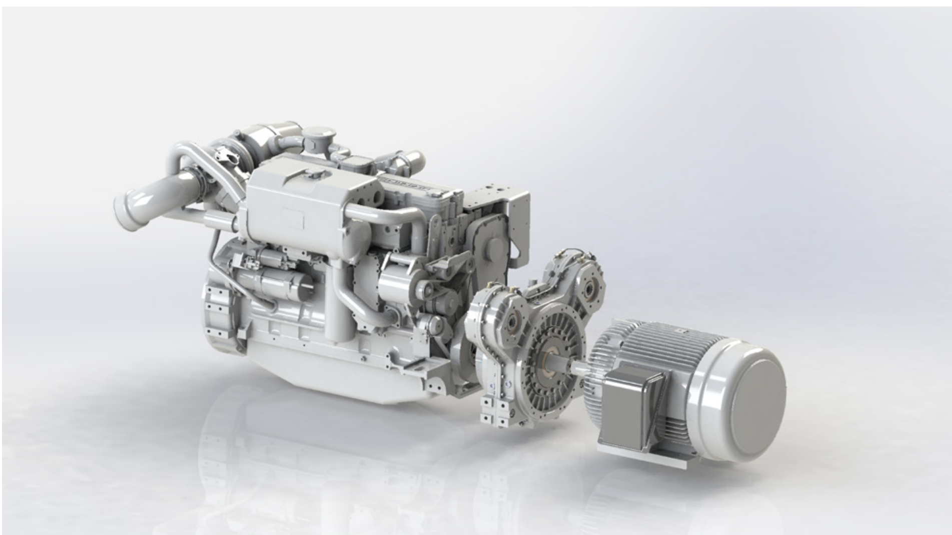


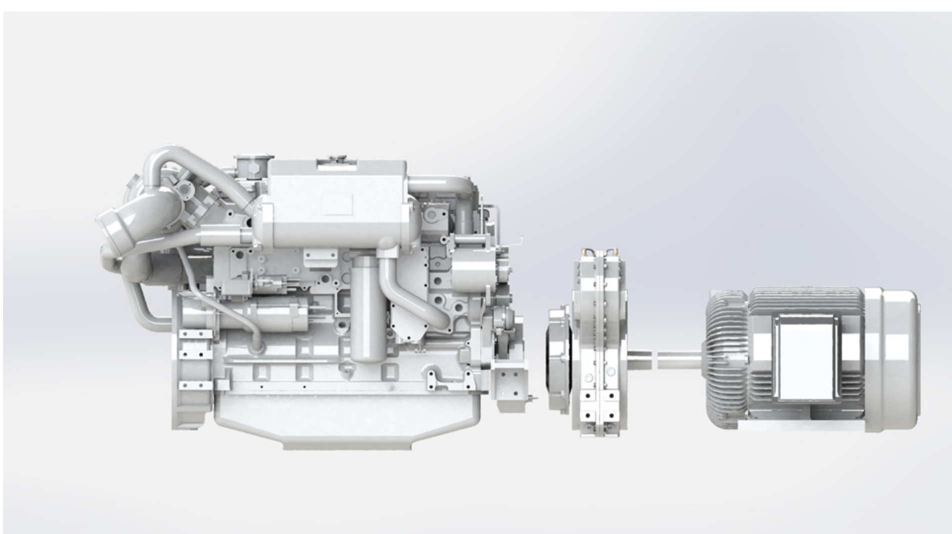
Front-of-Engine Applications

In some scenarios, it may be preferable to mount the motor/generator at the front of the main engine (opposite from the propulsion shaft). The motor/generator may be attached to a PTO/PTI tower position, as previously described, or directly in line with the engine as shown below.

In these applications the FlexaGen can be utilized as a source of electrical power. It may also be possible to contribute torque to the shaft using the motor/generator in PTI mode, although some consultation with Logan/Canal and with the engine manufacturer will be required.

Clearly this application is not suitable for electric propulsion PTI modes where the main engine is to be shut down.





Systems Integration

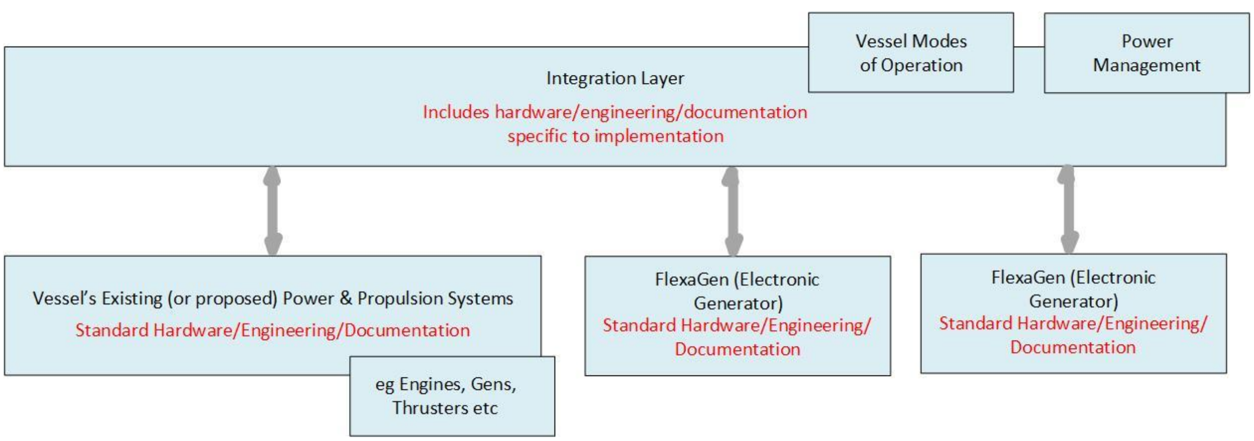
The FlexaGen is a clearly defined functional (and physical) unit. In other words, a 'standard' unit with the functionality and properties described in this document. It may be produced in a number of sizes according to power rating, but its functionality remains the same. This has the following advantages:

- Engineering costs are reduced because no 'job specific' engineering is required for each FlexaGen produced.
- Parts are standardized, allowing spares to be effectively managed and benefitting the purchasing process. Costs can be reduced (by procuring a smaller number of parts in greater quantities).
- Standard documentation can be perfected, without the need to update it on a job-by-job basis.
- Manufacturing is more efficient and quality benefits because there are no variances in the units produced.
- Standard test procedures can be perfected, with no significant departures on a job-by-job basis.
- Personnel can be given training in the installation, commissioning, maintenance and repair of FlexaGens, and they may become experts on these systems without the need for specific knowledge of each implementation.

It is worth emphasizing that each FlexaGen system produced is therefore optimized in terms of cost, documentation, spares and training. This benefits both the end-user and the Marine Integration Team. Each standard FlexaGen is fully featured for PTI and PTO functions (even where not all functionality is required for a particular job).

In order to perform a meaningful role in the vessel, each FlexaGen must be integrated with existing systems or, in the case of a new-build, with the other new systems being installed. Typically the interface will be with those systems that relate to the vessel's electrical power plant and/or propulsion. In some cases, controls may be needed to allow the crew to place the vessel into various modes of operation that utilize the FlexaGen system in different ways.

The 'Systems Integration Layer' is shown in the diagram below:

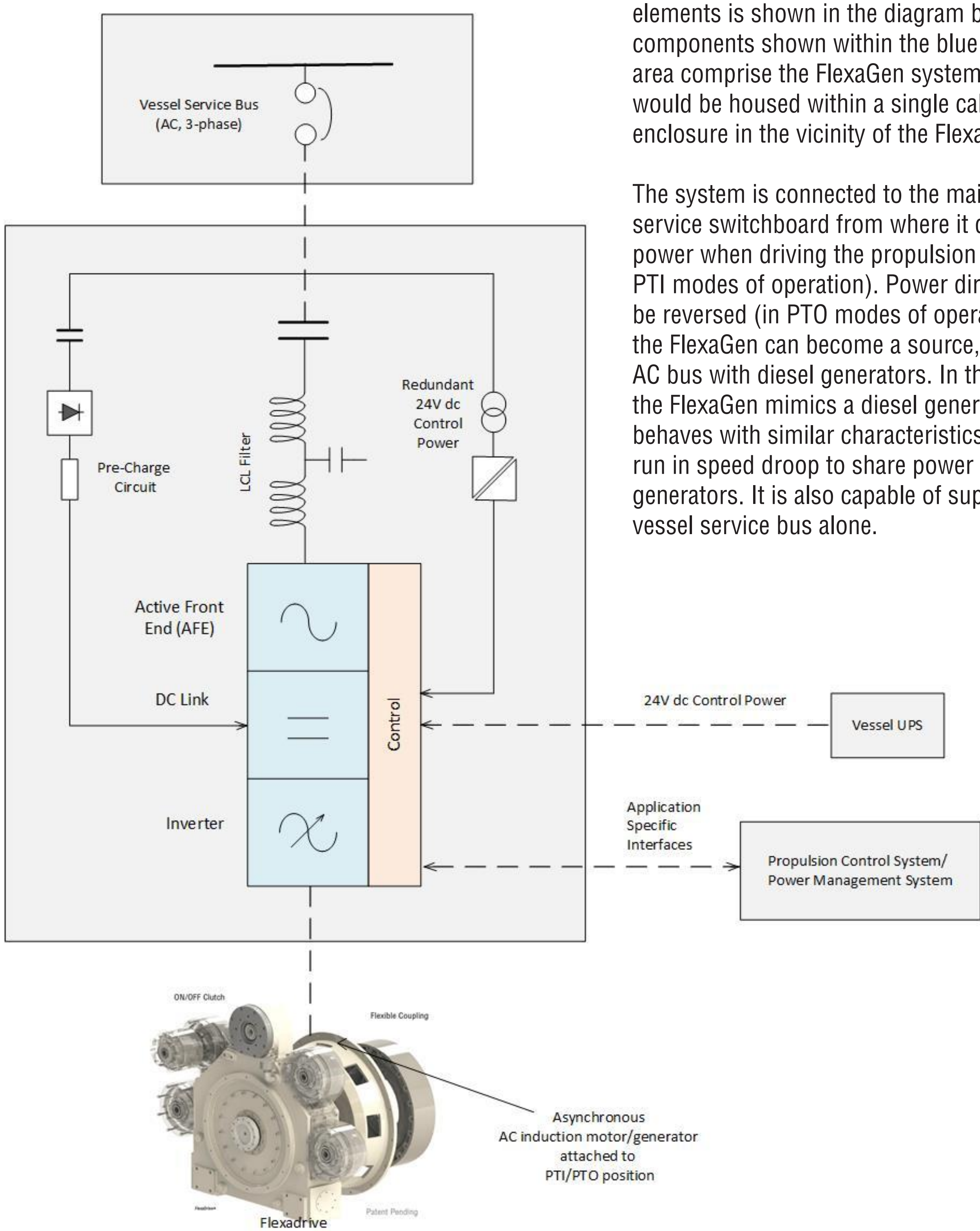


The Integration Layer typically consists of additional hardware, engineering effort, documentation and on-site commissioning and testing. This is the process of taking the standard FlexaGen and interfacing it with other systems to achieve the desired result. The other systems may be propulsion controls,thrusters/props, diesel generators, switchboards, alarm and monitoring systems, power management systems etc. The Integration Layer will be specific to each individual implementation of a FlexaGen. The Integration Layer can be provided by the Marine Integration Team, or by another Integrator with the required skillset and training, working with the documentation provided for the FlexaGen.

Functional Overview

An overview of the system showing the key elements is shown in the diagram below. The components shown within the blue shaded area comprise the FlexaGen system. These would be housed within a single cabinet/ enclosure in the vicinity of the FlexaDrive.

The system is connected to the main vessel service switchboard from where it draws power when driving the propulsion shaft (in PTI modes of operation). Power direction can be reversed (in PTO modes of operation) and the FlexaGen can become a source, sharing the AC bus with diesel generators. In this mode, the FlexaGen mimics a diesel generator and behaves with similar characteristics. It can run in speed droop to share power with diesel generators. It is also capable of supporting the vessel service bus alone.



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A suitable circuit breaker must be provided in the main service switchboard for connection of the FlexaGen. In the diagram above, this breaker is shown rated at 150A, corresponding to a FlexaGen power of approximately 100kW and based on a 480V plant. Other power ranges are available, and the above should be taken as an example only.

The standard FlexaGen package functions across a bus voltage range of 380V to 690V. Other voltages can be used, typically by adding a transformer with an appropriate ratio.

For retrofits, the AC switchboard circuit breaker may be pre-existing as a 'spare' in the vessel service switchboard, or it may be added as part of an 'integration package' accompanying the introduction of the FlexaDrive and FlexaGen. In some cases, it may be appropriate to add metering for the FlexaGen breaker at the AC switchboard. The FlexaGen is not simply a load. It may be a source in some modes of operation and as such, metering (volts, amps, frequency and power) may be required. This will come under the system integration workload. Metering and protection of other sources on the bus – typically diesel generators – is rarely affected and normally does not require modification.

A line contactor is used within the FlexaGen system to provide an additional (and automatic) means of isolating the FlexaGen's power converters from the AC bus. This allows the system to ensure that its internal capacitive elements are 'pre-charged' prior to connection of the main power, avoiding current inrush which can be damaging or lead to nuisance trips of the breaker. The FlexaGen's control of the line contactor also means that it can open it in the event of certain faults being detected (eg power converter trips, overloads, motor faults, over-temperatures etc). Fault current (short circuit) protection should be provided at the switchboard breaker.

The FlexaGen consists of two stages; a front end stage and an inverter (or variable frequency drive) stage. The action of the two stages depends upon the general mode of operation; PTI or PTO.

The FlexaGen can be produced in a range of power ratings, and several can be used together on a single FlexaDrive system. The functionality described in this document is accurate across the range of sizes.

Operation in PTI Mode

In PTI mode the motor provides a positive torque contribution to the main shaft, supporting propulsion.
The direction of electrical power flow is from the vessel service bus through the FlexaGen to the motor.
In this mode the role of the front end is to support the internal DC link which feeds the inverter (or 'VFD') stage. The front end acts as a voltage regulator, maintaining the DC link at a configured level.
Note that the DC link voltage exceeds the voltage of simple diode-rectified AC. As an Active Front End (or 'AFE') it is able to perform a voltage conversion and boost the instantaneous voltage applied at its input. The input LCL filter facilitates this voltage conversion. An additional benefit is that the AFE is able to mimic a resistive load on the AC bus, reducing harmonic distortion.

The VFD then controls the motor in a standard manner, using the DC link established by the AFE as its source. A speed, torque or power reference can be supplied from an external system (eg thruster control) and the VFD will follow this reference, subject to its configured limits. The VFD may be utilized to turn the shaft on its own through its corresponding motor, or in conjunction with other FlexaGens (motors positioned at additional PTO/PTI points on the FlexaDrive system). The VFD may also act to support the operation of the main prime mover (eg main propulsion engine) by providing a torque or power contribution. This leads to some interesting additional applications of the systems, such as boosting propulsion where main engines are undersized.

Operation in PTO Mode

In PTO mode the motor provides an opposing torque contribution to the main shaft, acting as a braking force on the shaft and generating power which is fed back to the vessel service bus. The direction of power flow is from the motor, through the FlexaGen, to the vessel service bus.

The VFD stage excites the motor in such a way that a braking force is applied. This is similar to the drive being in torque control with a negative torque reference. However, the VFD is configured to act as a voltage regulator for the FlexaGen's DC link. It applies enough negative torque and takes enough power off the shaft to maintain the DC link at the configured voltage. It does this at varying shaft speeds.

In this mode, the AFE is configured to be an AC regulator for the vessel service bus using the DC link as its source. It simulates the properties of a diesel generator and is able to run continuously in parallel with other FlexaGens (perhaps fed from alternative positions on the same FlexaDrive or from another propulsion shaft) or with diesel generators. The FlexaGen is able to self-synchronize with the AC bus and to support it in isolation if required (subject to configured power limits).

Gearing and Capacity

The gear ratio between the main shaft and each PTO/PTI drive can be selected to maximize performance under the required modes of operation. Higher ratios will allow more torque to be applied to the main shaft via an induction motor at the PTI/PTO position. This is true whether the induction machine is motoring (applying positive torques to the shaft) or generating (applying negative torque to the main shaft). A higher ratio maximizes the FlexaGen's ability to produce or consume power at lower shaft speeds.

It is envisaged that some applications of the FlexaGen will require as much power as possible to be available from the induction machine at relatively low speeds.

Example:
A vessel utilizes a 2000hp main engine on a propulsion shaft. The full speed of the main engine is approximately 1800 rpm. A FlexaDrive unit is installed with two induction motor/generators rated at 125hp each (for a total of 250hp). It is intended that the motors will be used to provide a 'get-home' function and also to act as generators when the main engines are driving the shaft (allowing auxiliary diesel generators to be shut down).

It is intended that the main shaft will be driven in the range 0-900rpm via PTI in 'get-home' mode (with main engine shut down and clutched out).

A 2:1 gearing is chosen between the motor/generator and the main shaft.

The motor/generators chosen are 4-pole asynchronous induction motors; meaning they produce their maximum power as their speed approaches 1,800 rpm. This means that their maximum power contribution is available as the main shaft speed approaches 900 rpm. It is important to understand that power is the product of torque and rotational speed. The motor/generator has a good ability to produce torque at lower speeds. However, its ability to produce power is limited. This is an important consideration if the FlexaGen is intended to produce power at lower shaft speeds. Power generation is possible, but not at the full rated capacity of the induction machine.

At motor/generator speeds above 1800 rpm (or 900 rpm on the main shaft), the torque capability declines gradually while the power consumption/production remains approximately constant. The induction machines can be used very effectively as generators at these higher shaft speeds, producing kW close to their nameplate ratings.

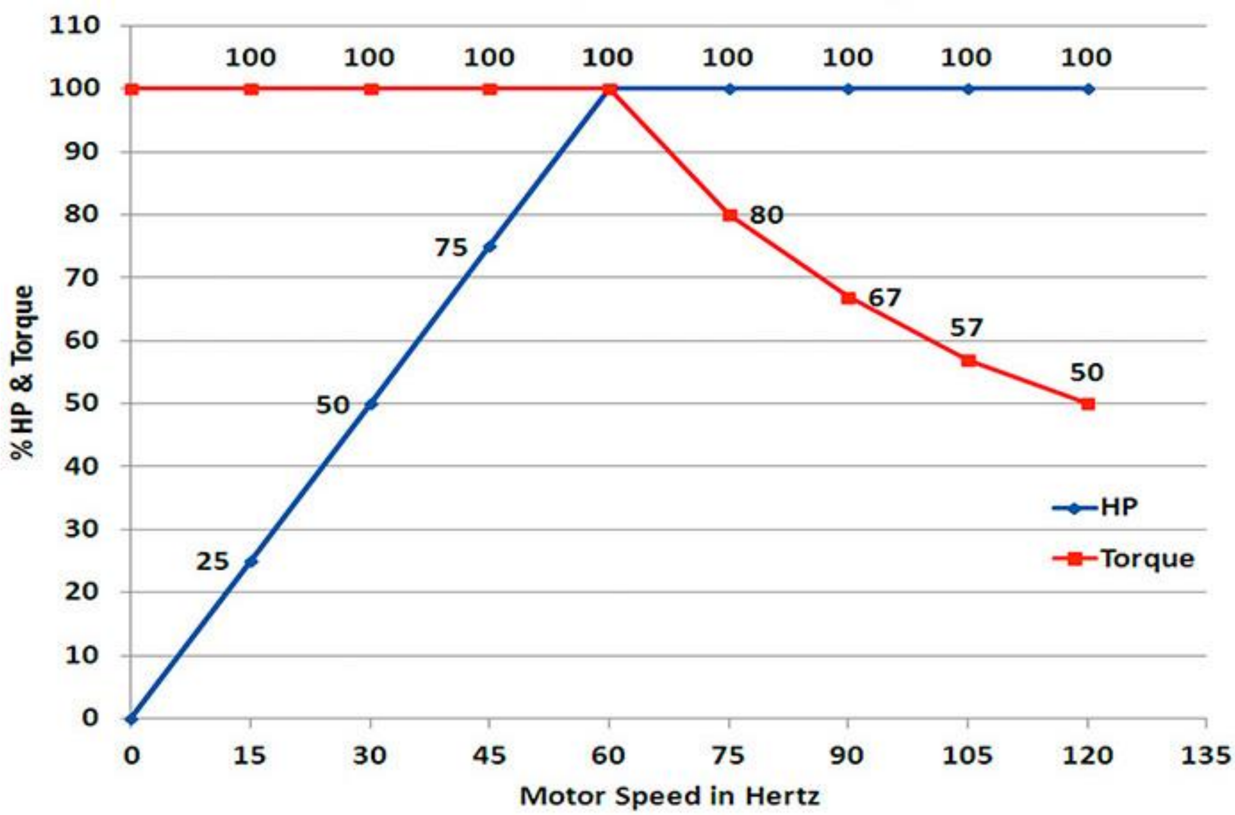
Note that the motor/generators are selected to be capable (mechanically) of rotating at the maximum shaft speed dictated by the main engine. In this example, 1800 rpm on the main would equate to 3600rpm on the motor/generator. This is considered at the design stage for each FlexaGen application. The power converters (inverters) controlling the motor/generators are easily able to operate (motoring or generating) with the motors spinning at these speeds (corresponding to 120Hz) or even higher. The ability to spin at these higher rates is solely a mechanical consideration. A suitable induction motor must therefore be chosen.

Understanding Motor Speed, Torque and Power (Induction Motors)

The principles relating motor torque, power and speed for a VFD-controlled motor are generally true whether in motoring or generating modes of operation.

The (simplified) diagram and explanation below will assist in understanding how much of a motor/generator rated power is actually available across a range of speeds. For the explanation below we assume motoring. Generating is similar but with opposite torque and opposite direction of power flow.

The VFD can provide rated current to the motor at low speeds. Torque is aligned with current and therefore maximum torque at low speeds is also fairly constant. As the motor speed increases, so does back emf (opposing the flow of current). However, the VFD has a “volts/Hz” ramp programmed into it, and it is therefore able to maintain rated current even as speed increases. Power – being the product of torque and speed – increases linearly with speed in this zone of operation. At motor nominal speed (1800 rpm for a 4-pole motor) the VFD completes its volts/Hz ramping and the motor current/torque begins to decline as speed is further increased, back emf increases and applied voltage can no longer be ramped up. Power remains constant in this zone.



This simplified explanation helps us understand how much power may be available from a motor/generator across a range of speeds. The key variables are:

- Motor poles (indicating nominal speed of motor at which rated power is available)
- Motor rated power
- The gear ratio between the FlexaDrive PTI/PTO position and the main shaft
- The maximum allowable rotational speed of the motor (generally a mechanical consideration)

It is suggested that the motor/generators – even though they are standard VFD-rated units – should be specified and supplied through the Marine Integration Team to ensure power expectations are met and to ensure compatibility with the FlexaGen and FlexaDrive systems.

Harmonic Distortion

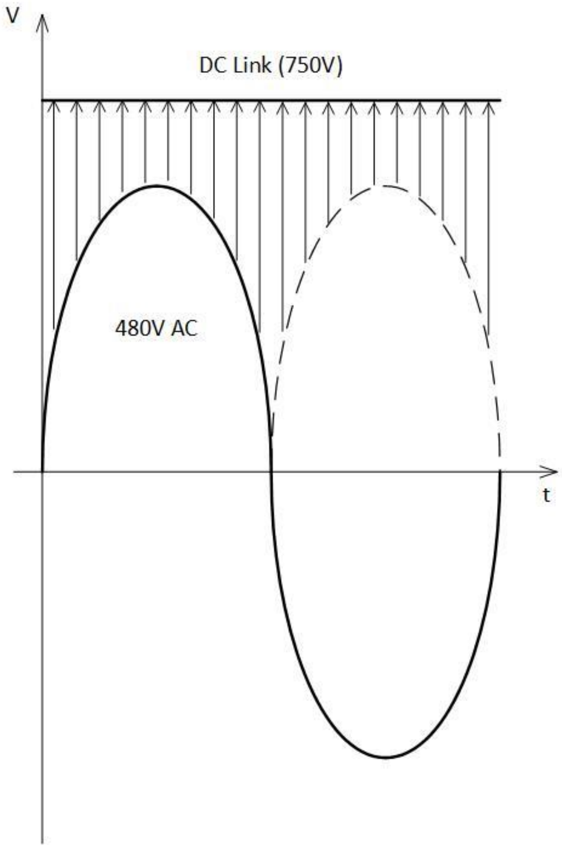
Systems that utilize a DC link for the support of large loads (eg props and thrusters) can typically be prone to high levels of harmonic distortion on the AC feed. Where simple bridge rectifier front ends are used to support VFDs, current flows from the AC side to the DC side only when the instantaneous AC voltage exceeds the voltage of the capacitive DC link and the rectifiers become forward biased. In other words the current is ‘pulsed’ through the front end. This failure to take power from every part of the AC input waveform results in a degree of ‘flat topping’. From the viewpoint of the AC plant, the front end would appear to be a nonlinear load, present only when the instantaneous AC input voltage is near the peak. The effect is most pronounced when the VFD-based load (eg propulsion motor) is significant in size compared to the AC source (eg diesel generator).

The harmonic content of the resulting distorted voltage waveform consists of the fundamental (eg 60Hz) but also includes content at higher frequencies. The significance of these harmonics depends upon the capacity of the source (AC plant / online generators) and the size of the DC load. The effect can also be somewhat mitigated by the use of techniques such as multiple phase-shifted transformer windings to produce 12-pulse arrangements (or higher).

The Total Harmonic Distortion (THD) for such a system can normally be predicted by calculation or by using electrical engineering analysis software. Marine regulations require THD to be less than 5% (unless it can be demonstrated that other loads on the AC bus are tolerant of higher levels).

The FlexaGen system makes use of a DC link within the VFD arrangement. This supports the inverter stage which provides a variable frequency AC output to the motor. However, the FlexaGen does not utilize simple rectifier front ends. Instead, Active Front End Converters (AFEs) are used. These are voltage converters capable of boosting instantaneous voltage on the AC side to produce an elevated, regulated and stable bus on the DC side. The converters are able to proportionally utilize the entire AC waveform so that they appear as a linear load and do not cause harmonic distortion (at least not on the scale of a simple rectifier front end). Fast microprocessor technology is used along with full IGBT bridges switching at 3.6kHz or higher. In many respects the front-end technology is similar to the inverter drive stage, although a line-side LCL filter is required.

The principal of operation is shown in the diagram below:



Note that the AFEs are also used in 'Island Mode' whereby they regulate the AC Bus, as well as in DC Bus regulation mode as described above. In other words, the converters are capable of bi directional power flow. When regulating the AC Bus, the units control the instantaneous AC voltage, again reducing THD on the AC side, even if non-linear AC loads exist.

Power Factor Correction

The Active Front End (AFE) is able to control the magnitude and phase angle of the line current with respect to line voltage. In other words it controls instantaneous current according to a reactive current reference. This reference is normally set during commissioning. A reference of zero reactive current causes the AFE to maintain its line current in phase with line voltage when supporting the DC Link from the AC feed (eg in PTI mode). In this way the FlexaGen mimics a resistive load. However, the reference can be adjusted to compensate – or correct – for other loads on the AC vessel service bus which would otherwise tend to create a non-unity plant power factor. The reactive current reference can even be derived from an analog signal, fed to the FlexaGen by an external power management system, with the aim of continuously (or 'actively') correcting power factor at the power sources. In this respect it can be a superior method to fixed passive filters (usually capacitive).

Please note that non-zero reactive current references can limit the ability of the FlexaGen to consume real power. The Active Front End is rated for line current, irrespective of whether this is real or reactive with respect to the plant. If highly positive or negative reactive current references are to be used then the AFE may have to be oversized in order to provide sufficient real power to the DC link.

Integration and Interfaces with other Systems

The FlexaGen system is provided with standard functionality to ensure that, as a product, it is consistent across a range of applications. This means that the product design is repeatable leading to consistency in parts and documentation. It is therefore easier to train personnel in the use and maintenance of the systems, even where they exist across a range of marine applications. Standard design leads to fewer parts used across a range of projects and makes it easier to provide support. It also reduces the cost of engineering, manufacturing, commissioning and supporting the products, increasing performance and value to the end user.

Between the standard range of FlexaGen systems and each specific application, a 'systems integration layer' exists. This should be viewed as a layer of engineering, documentation and commissioning that allows the FlexaGen to be integrated into the wider vessel system in order to achieve the required highlevel functionality. This integration layer may also include additional hardware elements. It frequently includes automation systems (PLCs and HMIs) and a programmed power management application.

A range of standard and configurable interfaces are included with the standard FlexaGen in order to facilitate integration with other systems, such as AC power plants, propulsion controls, or vessel power management systems. In general, not all of these interfaces are applicable to every implementation of a FlexaGen.

The 'hard-wired' control interfaces described in this section may be replaced by communications links in some applications of the FlexaGen. This is equally valid, and it is becoming an accepted means of marine system control (with the exception of some safety circuits, such as emergency stops).

Hardwired signals are assumed to be isolated at source. Typically a "volt-free-contact" is provided by the system originating a digital signal. Similarly analogue signals (4-20mA) are assumed to be isolated at source.

Use of an Isolating Transformer

In some cases, a transformer must be used between the Vessel Service AC feed and the FlexaGen. This may be required for the following reasons:

- The vessel plant operates at a nominal voltage that is outside the operating range of the FlexaGen unit (380V to 690V).
- The plant is not isolated from ground.

The FlexaGen must run isolated from ground. Most vessels use an isolated, ungrounded network (also referred to as an 'IT network'), at least for main three-phase distribution. This means that the main plant neutral is not directly connected to ground. In some cases the network may be grounded via impedance (to provide a means of detecting controlled/predictable ground fault current while preventing catastrophic energy release during such an event).

In general, an isolating transformer must be utilized between a FlexaGen and the vessel service bus if the main plant is grounded. If the main plant is ungrounded (or impedance grounded) it may be unnecessary to include an isolating transformer. This will be addressed on a case-by-case basis.

Use of VFD output filters

In some cases, a suitable filter (eg dV/dt type) is used between the VFD output of the FlexaGen and the motor/generator. This is generally true in any application where a VFD controls a motor (it is not a requirement peculiar to the FlexaGen system). These filters prevent the creation of high voltage spikes in the motor cables. The need for a filter depends upon a number of factors, including the distance between the VFD and the motor. Filtering requirements will be determined on a case-by-case basis.

24V dc Control Power (Vessel UPS)

The FlexaGen system requires a 24V dc control power feed from a vessel UPS system. This can be a grounded or ungrounded feed. Note that the FlexaGen also creates redundant control power internally from the 3-phase, 10A pre-charge feed. These two sources form a redundant pair. Pilot light indications on the door are included to show the status of each source.

Propulsion Control System

The FlexaGen accepts an isolated 4-20mA analog signal from a propulsion control system. This is used in PTI mode to indicate a speed, torque or power reference. Note that a torque or power reference is most appropriate when the FlexaGen is acting to support a main prime mover (such as an undersized main engine). A speed reference is typically used where the shaft is being driven solely by the FlexaDrive motor/s (supported by FlexaGens).

In cases where several FlexaGens are working together in PTI mode on a single FlexaDrive, it is normal to designate one as the 'master' unit and to provide the speed or torque reference to that one only.

Digital inputs can be provided to the FlexaGen from an external system (eg propulsion control system) to indicate that it should be in a certain mode (eg speed or torque control). In some cases, the signals can be used to indicate to the FlexaGen that it should treat the reference provided as a power reference.

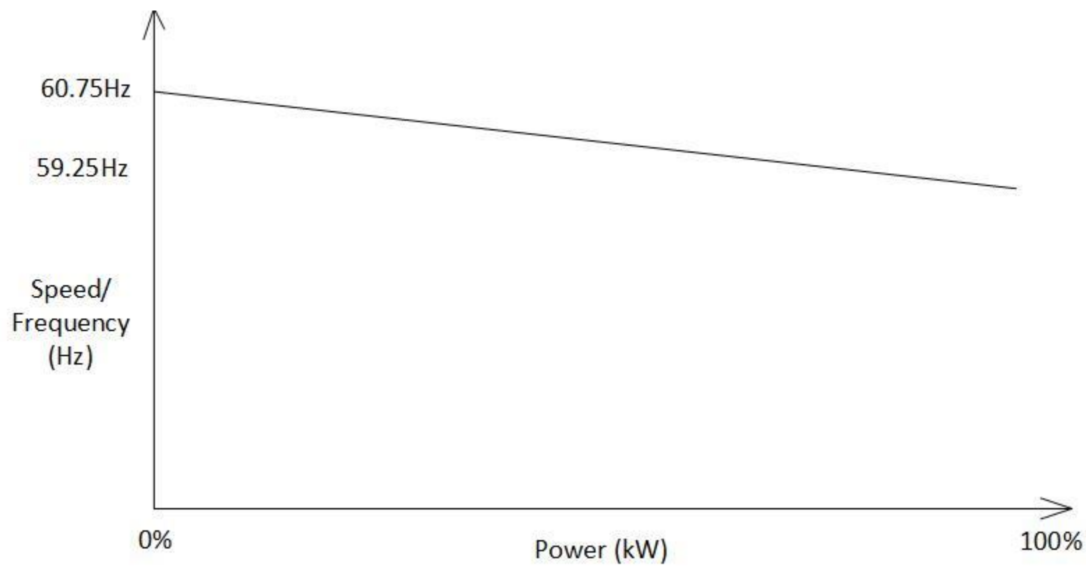
Power Management System (PMS)

A vessel's Power Management System (which may be considered a branch of a wider 'Vessel Management System') is responsible for high-level management of power resources. The system may not exist at all on simpler/manual vessels, while it can be quite comprehensive on more complex vessels. The Power Management System may be responsible for load dependent starts/stops of generators, load sharing and load shedding. Typically it provides the crew with a plant monitoring and configuration capability at a single console (allowing control through manual or automated means).

Clearly in many applications of the FlexaGen, which can act as a load or a source for the vessel power plant, an interface with the PMS will be required. This could be for the purposes of starting/stopping the FlexaGen or for changing its mode of operation (PTI/motoring or PTO/generating). In some applications, the PMS may provide a power reference to the FlexaGen via its analog I/O.

Load Sharing

For diesel generators sharing a common AC bus, a system of load sharing must be implemented. A FlexaGen mimics the characteristics of a diesel generator and is therefore able to participate in the load sharing scheme. Two methods are commonly used. One, known as speed droop, has the advantage of implementation entirely autonomously at each Diesel or FlexaGen. Each source has the 'droop curve' programmed into its governor (in the case of a diesel) or frequency control algorithm in the case of a FlexaGen. A typical droop curve is shown here:



Most off-the-shelf generator controls allow for use of such droop control in the speed regulation of the machine. We sometimes use the term "predictable droop" to emphasize that the generator output droops according to a specific model. This is important to differentiate from some existing installations where the no-load setpoint and droop percentage can be easily manually adjusted (where actual values are not critical as long as generators are observed to be load sharing). In particular it is important that speed bias is returned to predictable droop control after temporary operations such as synchronization of the diesel generator. The predictable droop characteristics should not be adjusted after commissioning.

When all sources – including all diesel generators and all FlexaGens on the common AC bus – are running in predictable droop they will load share. Control is autonomous and no communication is required between generator systems (unless the commonly observed frequency of the shared AC bus is considered a 'communication').

Implementation of speed droop also allows for additional plant functionality to be utilized (such as frequency based phase back of major loads described elsewhere in this document).

Alternatively, and very commonly in modern power plants, a form of 'isochronous' control is implemented whereby the fuel is controlled while ensuring load is shared and frequency is held constant (eg at exactly 60Hz). However, this method involves cross reference (communication) between individual generator functions. Sometimes 'load sharing modules' are used at each generator system. These monitor the local power contribution, cross reference against other sources, and adjust fuel accordingly.

In general, a FlexaGen is able to replicate the behavior of diesel generators in a wide variety of scenarios.

Special Purpose (Programmable) Interfaces

The standard design of the FlexaGen system anticipates several common applications. However, it is understood that many more applications are likely across a range of industries. For this reason, and to add flexibility for integrating the FlexaGen with external systems in general, a number of unassigned (programmable) interfaces have been provided. These are intended to provide flexibility in implementing the unit across a range of applications without the need for ‘special’ engineering or modifications to the core FlexaGen unit itself. Such modifications are possible, but will add cost to each project. It is preferred that the standard FlexaGen unit is used, including the configurable interfaces, with project-specific engineering being carried out within the ‘integration layer’ as described elsewhere in this document.

Connectivity (Monitoring and Control via Fieldbus)

Each FlexaGen system includes standard and configurable control interfaces for hard-wired signals. These allow control of the unit’s functionality (for example, start/stop and control of the direction of power flow). Basic monitoring can be performed using assignable outputs (for example; the status and health of the unit along with an analog signal that can be used to provide the magnitude of the power flow). These hard-wired signals are described in more detail elsewhere in this document.

In addition to the standard assignable hard-wired interfaces, each FlexaGen can be provided with a range of Fieldbus options. “Fieldbus” is a generic term used to describe a family of industrial networking protocols used within the control and automation fields.

Fieldbus connections can be used to allow the FlexaGen to be controlled. For example it can be started or stopped and regulated (provided with a ‘reference’ to control speed, torque or power). The FlexaGen can also be monitored, with a large number of parameters and metered values being made available via the communications link. In this way, a much larger amount of information can be communicated than would be practical using hardwired interfaces.

Fieldbus interfaces are important for the following reasons:

- As these technologies have matured through the late 1990s and 2000s, it has become far more common to control critical systems via robust, proven industrial Fieldbus links. This has the advantage of reducing and simplifying interface cabling and unifying many different systems from different vendors into a common interface design. Note, however, that it remains common – or required - for some critical marine functions (such as Emergency Stops) to remain hardwired.

- A trend exists (within the industrial automation and control field, including the marine sector) for many discrete systems to be “connectable” so that information can be consolidated at a common point (such as a vessel management system). Detailed information regarding a large number of vessel systems can be viewed and analyzed at a single console. Vessel systems data can be exported to a centralized ‘head office’ for fleet analysis and monitoring.

- In general a much larger amount of information can be monitored via Fieldbus than would be reasonably possible through hardwired interfaces. This could include internal temperatures, phase-by-phase voltages, currents and power, cumulative data (such as hours spent in certain modes or energy ‘trip counters’) etc etc.

Many modern vessel systems – such as engines – include industry standard communications interfaces, making large numbers of data points (temperatures, pressures, flows etc) available for centralized monitoring/logging. The FlexaGen is similarly able to communicate data using all common Fieldbus protocols including Profibus/Profinet, Modbus and CAN. Less common industrial automation protocols (for example AS-i, LonWorks, BACnet, Selma2) can also be implemented.

In summary, each FlexaGen will as standard include a number of hardwired assignable interfaces which can be used to control the unit or provide feedback (namely; six digital inputs, two analog inputs, three digital outputs, one analog output). Fieldbus communications interfaces will not be standard but can be included as options. In this way, the standard unit is not loaded-up with additional hardware that won't be required for every implementation. Implementation of a communications link to an external system will be included in the systems integration layer workload. This effort is considered similar to that involved in integrating other vessel systems (such as diesel engines).

Autonomous Functionality

While the FlexaGen responds to high level signals from external systems, it also has many autonomous functions which are implemented according to conditions detected locally.

Fault Detection and Mitigation

The FlexaGen system is autonomously capable of detecting internal faults, or problems with the propulsion motor it controls. It is also able to provide warnings while still running normally. Typically, the assignable I/O can be used to provide warning and fault signals to external systems (eg Alarm and Monitoring Systems) or to the system integration layer. The FlexaGen can even be configured to control external equipment based on autonomously detected conditions (eg automatic control of engine room cooling based on FlexaGen internal temperature).

Frequency-based phase back

In cases where the FlexaGen system is driving the shaft (PTI mode), it can be set to autonomously reduce its power throughput based on declining AC plant frequency. A measurable drop in plant frequency is often an indication of stress, overload, or a response to a significant step load. If the system is able to reduce its power consumption on such occasions, it will contribute to the stability of the plant as a whole. When this feature is enabled, the unit's power limit will be adjusted dynamically to decrease under proportional integral (PI) control. As the plant frequency recovers, the power limit recovers. This is an entirely autonomous feature of the local FlexaGen system. It does not rely upon signals from - or interfaces with - any external power management systems. The plant stress is communicated simply by the declining line frequency.

In cases where the plant frequency droops according to a defined 'droop curve' based on generator loading, the frequency based phase back may define the limit of PTI power. For example, the propulsion control sticks may be safely thrown fully forward and the PTI will run at maximum available power without overloading the generator. This is a completely autonomous function of the FlexaGen system and is based upon limits of plant frequency. As plant conditions change (loads come online or go offline) the PTI power adapts to maintain generator loading (or maintain minimum plant frequency).

Vessel Service UPS

The FlexaGen can be configured to act as an 'AC bus saver', autonomously detecting stress on the AC plant and swapping to AC bus regulation mode in the grid converter front end (even if it was previously acting as a torque contributor to the propulsion shaft). If the FlexaGen is being used with energy storage (eg a battery array in a hybrid power and propulsion system) then it can autonomously swap from charging to supporting the AC bus. This transition typically takes just milliseconds.

Like many of the capabilities of the FlexaGen, this is a configurable feature that may be useful in some applications of the system (but does not need to be enabled in all scenarios).

Load Shedding

Where a FlexaGen system plays a role in supporting a vessel's AC plant, either alone or in parallel with diesel generators, there is a danger that it may become overloaded. Just like a diesel generator, the FlexaGen has a rated capability to supply power. It also has an overload capability, although the characteristics differ from a typical diesel generator. If the FlexaGen has been previously running at its capacity in normal ambient conditions, then its overload capability is approximately 110% for one minute. It can exceed this if it was not previously running at capacity. The performance is based upon internal thermal measurements (not calculated directly from power and time). The short term overload output is 500% for 3 seconds (useful for ensuring protection devices are tripped in the event of a fault).

In the event of an overload, the FlexaGen can autonomously produce a 'load shedding' signal, available to an external power management system or load shedding system. This signal may be used to reduce plant loading. The signal is valid whether the FlexaGen is supporting the plant alone or in parallel with diesel generators. Implementation of this signal should be determined as part of the systems integration workscope.

Synchronization

Synchronization is the process by which two independent sources of AC power can be connected in parallel on a common bus. In the vast majority of marine cases, the sources are diesel generators. Typically the AC voltage setpoints are well enough matched to allow connection of generators to the common bus. The voltage controls (automatic voltage regulators or 'AVRs') are typically set to droop voltage according to reactive power, ensuring stability of the diesel gens on a common bus.

Generator frequency (speed) is regulated by adjusting the fuel control (or speed 'governor'). When multiple generators are connected in parallel on a common bus, their speed (frequency) is locked to that of the common bus. Adjusting fuel input up or down then increases or decreases each generators shareof real power. Load sharing measures are required. These can include the use of droop or of loadsharing modules which bias the fuel input of each gen to maintain equitable sharing of power on the bus.

Prior to connecting a diesel generator to the common bus, a synchronization process is normally carried out to ensure that the output of the additional generator matches the common bus in both frequency and phase angle. This ensures that no significant voltage differential will exist between the bus and generator phases at the instant of connection. Connecting an unsynchronized generator to the common bus can have serious consequences (in some ways similar to the effect of a short circuit).

Synchronization of diesel generators is normally accomplished using a specialized 'synchronizer' module. This monitors the frequency and phase of the generator and sends a bias signal to the speed governor in order to bring it in synchronization with the common bus. This is a process that can take several seconds. When the synchronizer sees that the target generator matches the bus – in other words it is of exactly the same frequency and there is no significant phase difference between the two – it issues a close permissive allowing the generator breaker to be closed. Once connected, the synchronization speed bias signal is removed and the diesel generator returns to its normal load sharing regime (either running in droop or controlling fuel according to a reference from a load sharing module).

A FlexaGen system is able to mimic a diesel generator and support a common bus in parallel with other diesel generators or FlexaGens. However, the method of connecting a FlexaGen to the common live bus can be much simpler than that required for a diesel gen.

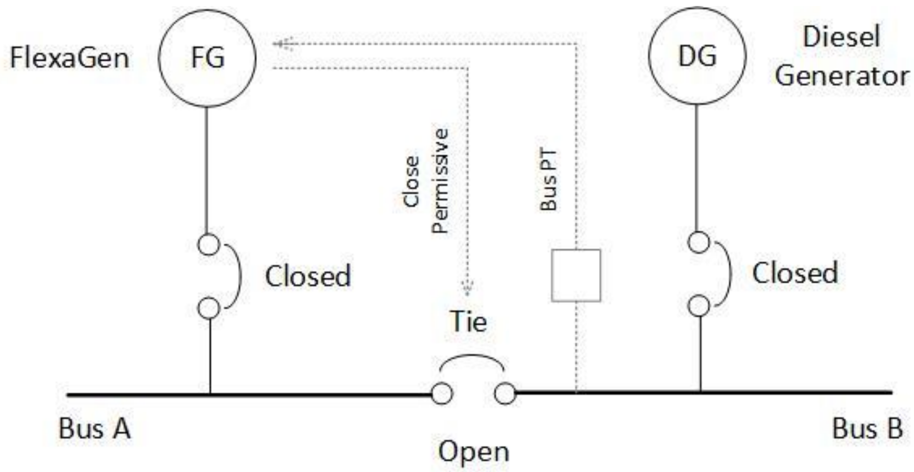
Initially the FlexaGen can be connected to the main bus at any time, without the need for a synchronization process. This is described elsewhere in this document under the heading "Enabling the System". At the time the connection is made, the FlexaGen appears as a small load. Once connected to the common bus, the FlexaGen can be instructed to act as a generator. It will then self-synchronize its own output with the bus as it ramps up. This is achieved electronically, through control of transistor gating. In other words, a separate synchronizer module is not required in order to bring a FlexaGen online on a common bus.

In cases where a FlexaGen must be synchronized across a tie breaker, it is obviously unable to self-synchronize by detecting the bus voltage at its line input. In this specific case, it must be provided with a voltage signal from the opposite bus, and it will then be able to match its output and issue a close permissive for the tie breaker.

In the case shown, the FlexiGen is supporting bus A and a diesel generator is supporting bus B. When closure of the tie breaker is required, the Flexigen is able to synchronize its output to the signal provided from the opposite bus. It can then issue a close permissive to the control circuits of the tie breaker.

Synchronization with a utility feed (such as shore power) is also possible with a FlexaGen.

Note that synchronization of the FlexaGen does not require an external synchronizer module (as typically used to synchronize diesel generators). Also worthy of note is the fact that – while synchronizing diesel gens can take several seconds – a Flexagen, which is an 'electronic generator', is able to synchronize its output in a fraction of a second.



Local Controls, Metering and Indications

Several controls, meters and indications are provided on the FlexaGen door as shown below.

Enabling the System

The "Main Power Present" pilot light (green) indicates that the incoming three phase supply is detected. If this is not illuminated it is likely that the circuit breaker feeding the FlexaGen from the main AC switchboard is not closed or, alternatively, that the main AC switchboard is dead.

The system cannot be enabled until the main incoming power is present.

An enable switch on the FlexaGen cabinet door brings the system online. The dc link is pre-charged from the 3-phase control power feed and the line contactor is closed. Note the following:

- The pre-charge process typically takes a few seconds. During pre-charge the "Pre-Charge in Progress" pilot light (yellow) illuminates
- Upon completion of the pre-charge process, the line contactor closes. Normally this is audible. The "Line Contactor Closed" pilot light (green) illuminates and the "Pre-charge in Progress" pilot light goes off.

If – for whatever reason – the pre-charge process is not able to complete within a timeout period, the system will cease attempting to bring up the DC-Link. The "Pre-charge in Progress" pilot light will go out and the "Fault" pilot light (red) will illuminate. It will then not be possible to attempt pre-charge again until the enable switch if first moved manually to the disable position.

The enable switch has two positions; enabled and disabled. When in the disabled position the FlexaGen opens the feeding automatic breaker (or line contactor if applicable) and the internal dc link is allowed to discharge. Even if disabled, the main cabinet section should not be accessed for five minutes, to ensure the capacitive dc link is properly discharged.

Although the FlexaGen has the ability to be remotely controlled once enabled (eg run/stop), the initial enable process as described above can only be performed manually and locally at the door.

Analogue Power Meter

An analog bi-directional (center zero) power meter is included on the FlexaGen door. The meter is scalled to +/- 150kW. The positive direction of power flow is considered to be in the direction of the FlexaDrive. In other words, the FlexaGen is considered to produce positive power when a PTI mode of operation is being used. When braking, or acting as a power generator (PTO modes), the system is producing power (or consuming negative power).

Note: In modes where the FlexaGen feeds power to the AC plant (either alone or in parallel with diesel gens or other FlexaGens), it may be appropriate to include additional metering at the main switchboard. This would be a consideration within the systems integration package accompanying implementation of a FlexaGen system.

Emergency Stop

An Emergency Stop (or 'E-Stop') button is provided on the FlexaGen door. This will cause the FlexaGen's VFD to stop running immediately, removing torque from the motor/generator. Note that the motor/generator attached to the FlexaDrive will then behave in a 'coasting' manner (power removed).

An emergency stop condition is considered a system fault. For example, it will lead to the red fault indication LEDs on the VFD keypad being illuminated (and the converter will be disabled).

Manual intervention is required to recover from an E-Stop condition. The E-Stop button is latching and must be returned to its non E-Stopped position. Manual reset at the converter keypad is also required.

Note that a provision is made for an optional remote E-Stop (or multiple remote E-Stops). This is described in the section dealing with interfaces.

Pilot Light Indications

The following pilot light indications are provided on the FlexaGen door:

24V PS OK (Green)
The FlexaGen creates 24V control power for its internal systems from the incoming three phase supply. This is achieved with a 1000VA control transformer and a switching power supply. This pilot light indicates the presence of the control power.

24V UPS OK (Green)
This indicates that the redundant 24V dc control power feed (from external vessel UPS) is present.
Note: The FlexaGen will function normally with either of the above control power sources present. However, for redundancy, it is recommended that both sources are healthy (both pilot lights illuminated during normal operation)

PRE-CHARGE IN PROGRESS (Yellow)
This indicates that the pre-charge process is active.

FAULT (Red)
In the event that a pre-charge operation fails, this pilot light indication will be illuminated. The indication will remain until the system is reset by returning the enable switch to the disable position.
Note that this fault lamp is not generally used to indicate faults within – or detected by – the power converters (AFE or VFD). Red Fault LEDs are included on the converter keypads for this purpose (see keypad description below).

LINE CONTACTOR CLOSED (Green)
This indicates that the line contactor has closed (as a result of a successful pre-charge operation).

MAIN POWER PRESENT (Green)
This indicates that the three-phase power feed from the Main AC Switchboard is present. This is a precondition for a successful pre-charge operation.

RUNNING (Green)
This indicates that the FlexiGen is running, meaning that the VFD is gating and the motor is being controlled.

Active Front End and Inverter Keypad Indications

Each of the two power converters comprising the FlexaGen (the Active Front End and the Inverter) has a keypad control mounted on the door. The detailed functionality of this keypad will be described elsewhere. It has no role in routine operation of the FlexaGen system. However, the three LED indicators – ready (green), run (green) and fault (red) – provide a useful overview of the system status.

Ready – Indicates that the converter is ready to run. There are no active faults and the DC link is at a suitable voltage.

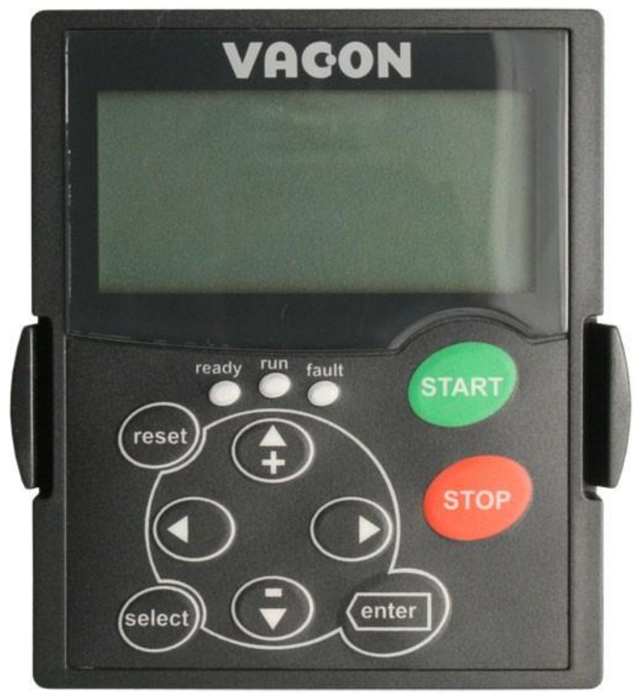
Run – Indicates that the converter is in a running state (ie it is 'gating' or switching its internal transistors allowing controlled regulation or current, voltage or power)

Fault – Indicates that a fault condition has occurred and the converter is disabled (will not run). Even after removal of the fault condition, the reset button on the keypad must be used to reset the fault. Note that E-Stop conditions are considered faults.

It is possible to use the keypad to browse useful information regarding the converter:

- Current and historical faults
- Parameter values
- Metered values (eg temperatures, speeds, power etc)

In general – where the individual FlexaGen is part of a wider 'Integrated System' – the most important information will be made available much more conveniently via the graphical user interfaces on the Human/Machine Interface (HMI) screen. If it is necessary for the crew to use the local FlexaGen keypads to check or monitor a value or status, the Marine Integration Team will provide instructions on a case-by-case basis.



The FlexaGen's Environment

In order to operate correctly on a continuous basis, the physical environment – both within and outside the FlexaGen's enclosure – must be controlled.

Ambient Temperature

The FlexaGen is rated for an ambient temperature of 45C. In other words, the nameplate rating of the system should be achievable on a continuous basis if the environment is maintained at or below this level. Please note that the FlexaGen is rated lower for continuous current than the apparent rating of the individual power converters within. This allows for the fact that air temperature inside the enclosure will be slightly higher than outside.

At temperatures above 45C, the FlexaGen can still operate, although its maximum rated current will be reduced. Warnings are provided from the FlexaGen based on internal converter temperature, not ambient temperature. Internal temperature depends upon ambient conditions, but also upon average current over a period of time.

Cooling

The FlexaGen uses two fans to draw air into the cabinet. Positive pressure is created within the cabinet causing warmer air to escape via the twin vents at in the top of the door.

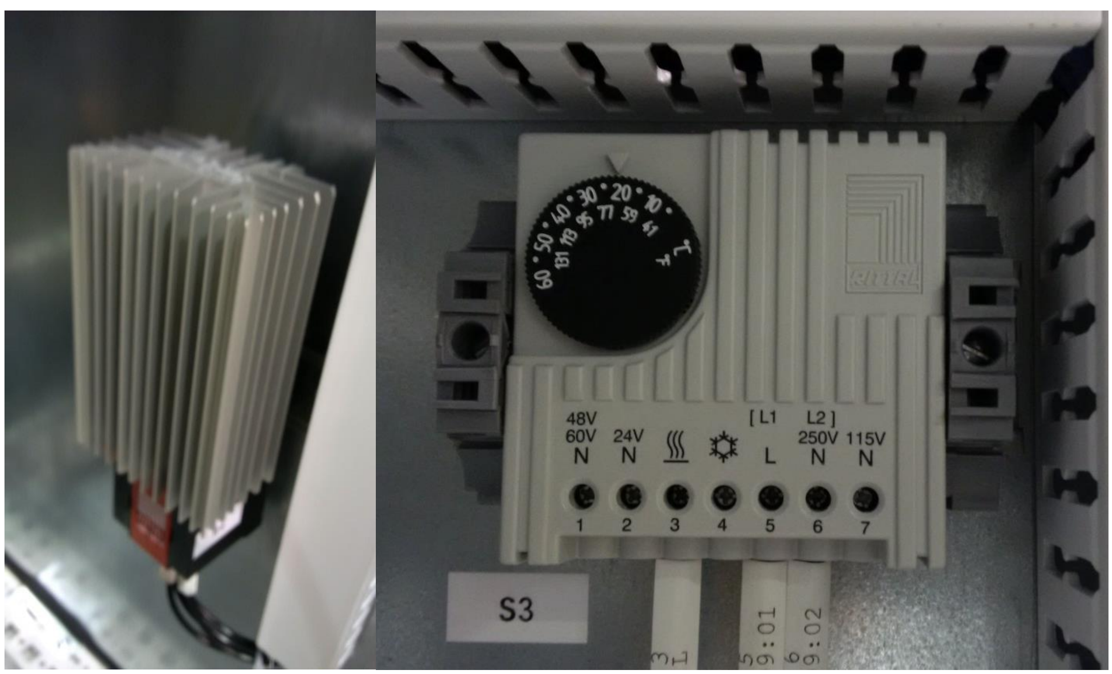
The first fan (left of door) starts whenever the FlexaGen has been successfully enabled (DC link precharged and line contactor closed). The second fan (right of door) starts when the VFD stage is running.

It is very important that the filters associated with both the fan units and the vents are replaced periodically to ensure air is allowed to flow as intended. Replacing them weekly is recommended, although more frequent intervals may be required in some environments.

Note that the individual power converters within the enclosure have built-in fans to draw air across their internal transistor array heatsinks (also known as 'stacks').

Heating

The FlexaGen cabinet includes a heater to ensure that moisture does not accumulate during dormant periods. This is a common occurrence within marine electrical system cabinets left dormant (during periods of maintenance or vessel inactivity). It should be taken very seriously as moisture can pose a significant threat to the internal power converters. The FlexaGen is provided with a heater and thermostat as pictured below.



The heater power is provided from an external source (typically 110V ac to 240V ac). This source should be separate from the main power used to feed the FlexaGen. It may be necessary for the enclosure to be heated at times when the main source of power has been removed (eg during maintenance periods).