Integrated thruster control – total solutions for electrical power and automation in the marine sector

ABB has developed an integrated thruster control system with significant operational and cost benefits for the marine and offshore sector. It incorporates a dynamic positioning system (Dynpos), a thruster-assisted position mooring system (Posmoor) and an automatic sailing system (Autosail). As a leading supplier of electrical power and automation equipment to this market, ABB can now offer total integrated solutions for improved performance and reliability as well as minimized energy consumption and CO_x/NO_x emissions.

Until recently, huge oil and gas resources were accessible in shallow water and could be exploited by fixed drilling and production units. In the North Sea, as in several other areas, the new resources are found in smaller and less available fields at greater water depths. For these fields, more cost-effective solutions based on floating concepts for deep-sea drilling, floating production and loading have become available as a result of sophisticated dynamic positioning systems and thruster-assisted position mooring systems. The power needs of position-keeping and heading-keeping systems are considerable due to the heavy sea and wind loads acting on the vessels. Typically, the installed thruster power is in the range of 12 to 40 MW. Together with the production, drilling, utilities and other loads, the total installed power may be as much as 25 to 50 MW.

The high demands made on vessel performance, environmental compatibility and overall safety have resulted in more attention being given to the total vessel concept and the interaction between the equipment and systems installed. Greater operational flexibility is achieved with electric power generation and distribution systems for propulsion, positioning, oil production, drilling and loading that integrate all the equipment and control systems in a common power plant network and automation network.

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Positioning systems have been commercially available for marine vessels since the 1960s. However, it is only in the 1990s that fully integrated electric power, automation and positioning systems have come onto the market. In the international marine, oil and gas sector, ABB is one of few vendors able to offer such solutions. Its uniqueness as a total supplier with standard in-house products is applied to creating the optimum solution – for the customer and for the environment – in terms of vessel mission, energy consumption and safety. However, there is still a considerable potential for cost-saving and energy optimization which can be tapped by applying new solutions based on so-called 'in-between technology' in the fields of control, electric power and marine, oil and gas technology. ABB is addressing these issues with substantial R&D efforts.

ABB Integrated Thruster Control System

The newly developed Integrated Thruster Control System (ITCS) comprises the following different types of positioning systems for use on floating vessels **1**:

- *Automatic sailing (Autosail)* system for automatic course-keeping and course-changing during transit operations
- *Dynamic positioning (Dynpos)* system, providing manual or automatic positioning via the thruster system
- *Position mooring (Posmoor)* system, providing manual or automatic thruster assistance for position and heading control of anchored vessels
- *Manual thruster control (MTC)* system, for individual control of the thrusters and propellers

In addition, several operator advisory systems for operational consequence analysis, planning and training have been developed.

Control system configuration

The integrated thruster control system is implemented on standard ABB hardware and software platforms. The process controllers, operator stations, information management station and networks are chosen according to the data processing, memory and I/O capacity and safety requirements. The operator consoles are designed to meet the requirements of marine installations. The consoles can be connected in different configurations to satisfy the needs of the different vessels. Gyrocompasses are used to measure the vessel heading, and so-called motion reference units (MRUs) provide measurements of vessel heave, roll and pitch motion. Taut wire, Artemis, differential GPS/Glonass, hydro-acoustic position reference (HPR) and laser beam systems are typically used to measure a vessel's position. Different environmental sensors for measuring wind, current and wave data may also be installed. The thruster, rudder, mooring (if any), sensor and control system configuration varies for each type of vessel concept and class.

A typical ITCS configuration for a drilling rig is shown in **2**. The illustrated system complies with Dynpos Class 3 and consists of a refined duplex control system (A, B) and a single back-up system (C). Two dedicated consoles are for the manual thruster control (MTC-A, MTC-B), one each is for operating the Dynpos, Posmoor and Autosail systems (DPCON-A, -B and -C), one is for the consequence analysis (SIM/CQA), and another is for operating the HPR system. Operator training is facilitated by connection of the ITCS training simulator to the backup system.

The Autosail, Dynpos and Posmoor systems can be operated in several different modes. At any given time one of the sub-systems will always be in operation. When the operating system is in the initial mode the thrust devices may be controlled via the manual thruster control (MTC) system.

Offloading oil/gas from a turret anchored floating production unit **1**

Autosail system

The Autosail system **3** is used for long-distance sailing and has the following main operating modes:

- *Autopilot:* for automatic course-keeping and course-changing via control of the thruster azimuth angles and rudders.
- *Course correction:* for correcting the course set-point in response to environmental disturbances and drifting.
- *Tracking:* a high-speed, way-point tracking function used for long-distance sailing. The tracking mode is used to follow, via control of the thruster azimuth angles or rudders, a track pre-defined by way-point coordinates.

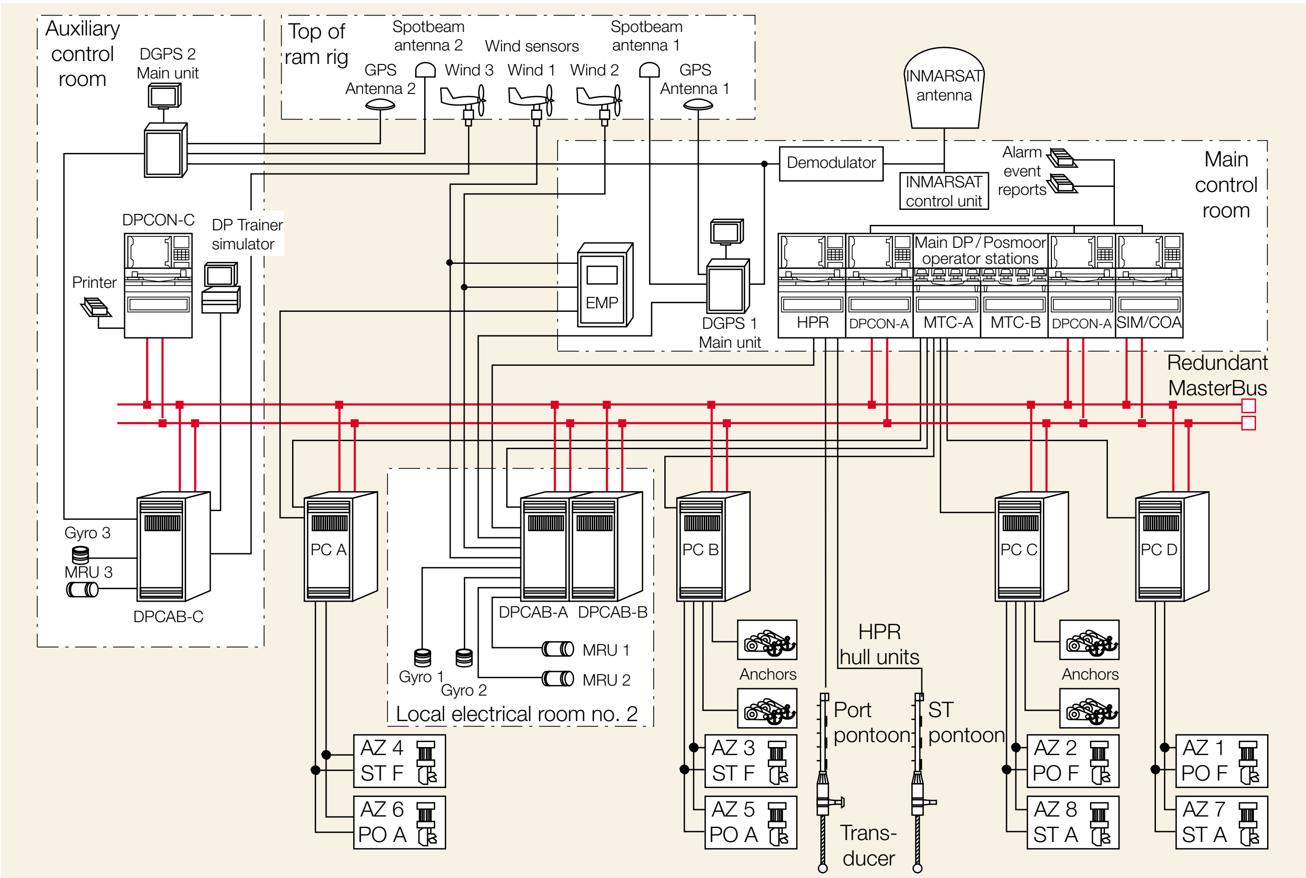
The way-points and velocity setting can be changed at any time by the operator, who can also specify the maximum angular velocity, off-track alarm limits and maximum rudder or azimuth angle.

Dynamic positioning system

The Dynpos system is for manual and automatic positioning via operation of the thruster and rudder system. The Dynpos control functionality is closely connected to the surge, sway and yaw degrees of freedom (DOF) **4**, which can be viewed as being independent of the actual thruster configuration. Hence, the Dynpos system allows either manual (joystick) or automatic control of each degree of freedom.

The Dynpos system **5** offers the following main modes of operation:

- *Init:* for configuration, initialization and supervision of the Dynpos system.
- *Manual:* in this mode all 3 DOFs are controlled manually using a joystick.
- *Semi-auto:* a combination of manual and automatic control of the surge, sway and yaw.



A typical configuration of the integrated thruster control system, Dynpos Class 3 **2**

AZ *Azimuth*
DGPS *Differential global positioning system*
HPR *Hydro-acoustic position reference*
MRU *Motion reference unit*
PO *Port*
ST *Starboard*

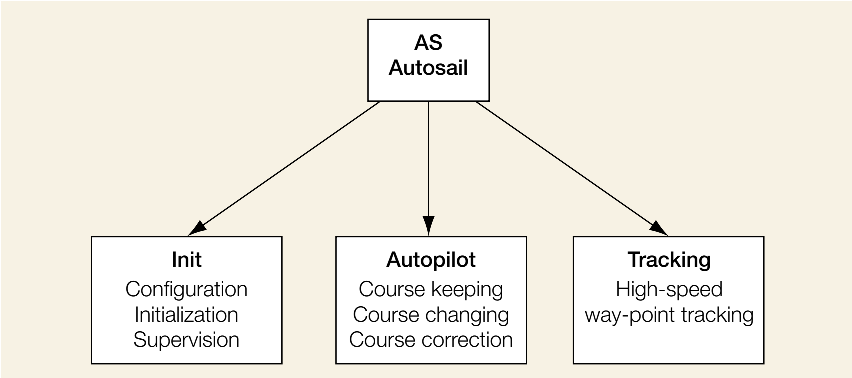
- In *auto mode* all 3 DOFs are controlled automatically by the control system. Its functions are:
  - *Station-keeping:* to maintain a fixed position and heading for the ship.
  - *Marked position:* tracking control in all 3 DOFs; the vessel moves from one position and heading to the new position and heading in accordance with set-points given by the operator.
  - *Weather optimal positioning:* keeps the position fixed while the heading is automatically updated; minimizes environmental loads acting on the vessel.
  - *Tracking:* low-speed, way-point tracking function used when the vessel is to follow a trajectory defined by a set of way-points. 'Follow ROV[1)]' is a tracking function in which the vessel follows an ROV according to given set-points.
- *Roll and pitch damping:* to suppress roll and pitch oscillations induced by thrusters or environmental loads. It can be enabled in all auto mode functions.

Position mooring system

The Posmoor system is used for manual or automatic thruster assistance when the vessel is anchored to a mooring system. In position mooring, thruster assistance is complementary to the mooring system. Normally, most of the station-keeping in surge and sway will be provided by the mooring system. The system functionality is similar to that of Dynpos, but there are some additional control functions to take account of the position mooring. As in the Dynpos module, the control functionality is closely connected to the surge, sway and yaw degrees of freedom. Hence, each degree of freedom is controlled either manually or automatically by the Posmoor system, and a corresponding force/moment set-point is generated. Like Dynpos, the Posmoor system has 4 different main modes of operation: 'init', 'manual', 'semi-auto' (any combination of manual control and automatic control of surge, sway and yaw) and 'auto' **6**.

Damping control may be used in any of the 3 DOFs to reduce any large oscillatory

[1)] ROV = Remotely Operated Vehicle



Autosail modes and functions **3**

motion and thus reduce possible stress acting on the mooring system.

'Watch circle control' is a monitoring function for use at times when the thrusters are switched off. When the ship's position or heading exceeds certain predefined limits or irregularities occur the thruster system is started and the station-keeping function is enabled.

Operator advisory systems

These assist the operator by ensuring safe and efficient running under the prevailing operating and environmental conditions. In addition, simulators for predicting and planning future operations have been developed.

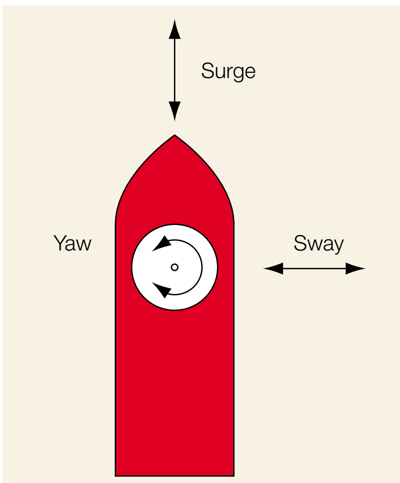
Dynpos consequence analyzer

The Dynpos consequence analyzer is a separate module, interfaced to the database of the controller for the exchange of all relevant parameter, measurement and control data. It describes the actual control configuration and determines the prevailing operating conditions. The consequence analysis evaluates the ability of the remaining thruster configuration or power system to produce an adequate resultant thrust vector after a 'maximum single failure' has occurred. The 'maximum single failure' is defined for each specific system design. Typical cases are loss of one switchboard, one engine, or a group of thrusters (common failure mode). The analysis considers the average power and thrust consumption, and is performed continuously for all defined failures in any sequence. Positioning capability plots are calculated which show the effect of the different failure scenarios.

Dynpos simulator

The Dynpos simulator is a separate advisory system for the Dynpos system. It performs off-line simulations for the calculation of thruster capacities and vessel dynamics for operation planning under the prevailing and forecast environmental and operating conditions. It interfaces the database of the ITCS controller to read the relevant system parameter, measurement and control data used to describe the actual control configuration and to determine the prevailing operating conditions. The Dynpos simulator can also be used for so-called drift-off and drive-off analyses.

Surge, sway and yaw effects acting on sea-going vessels **4**



Posmoor consequence analyzer

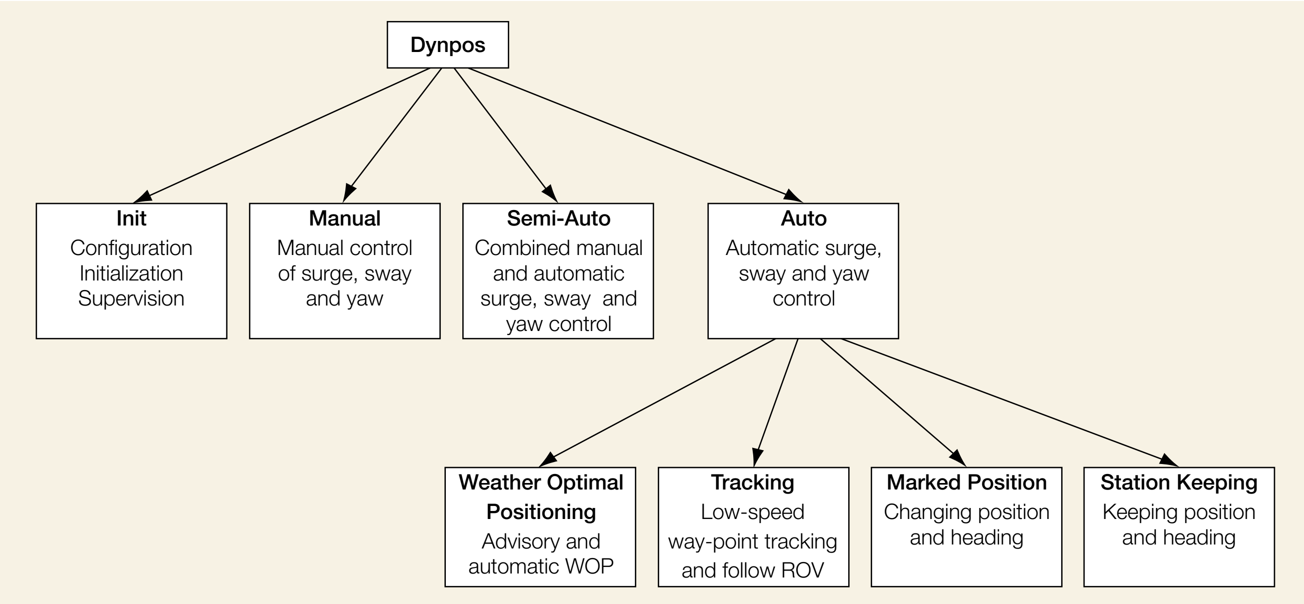
The Posmoor consequence analysis is performed at given intervals for all defined single failures in sequence. It determines the way in which any single mooring line or thruster failure will effect vessel and mooring behaviour.

The consequence analyzer reads the prevailing operating and environmental conditions from the Posmoor process control station (via the data highway) and determines the consequences. When these are unacceptable, an alarm is given.

Posmoor simulator

The following simulations can be run on the Posmoor simulator:

- *Mooring conditions:* determination of anchor positions and vessel equilibrium position based on line pre-tension and line direction; no account is taken of the environmental loads.
- *Environmental effects:* calculation of line tension, vessel offset and vessel low-frequency and wave-frequency motion, based on wind, current and wave loads.
- *Failure:* graphical representation of a time series calculation of line tension and vessel motion over a specified time period in the event of line breakage or thruster failure.
- *Tension optimization:* calculates the winch run for optimum tension for each line based on desired pre-tension for all lines; the vessel position remains unchanged.
- *Re-positioning:* calculates the winch run needed to re-position the vessel without affecting the line tension. The operator can specify operating and environmental conditions for the simulation, when required in combination with data about



Modes and functions of the dynamic positioning system, Dynpos **5**

prevailing conditions from the Posmoor controller.

ITCS trainer simulator

An ITCS trainer simulator has been developed for training operators in the use of Dynpos and Posmoor. It can be delivered as a stand-alone system with separate console or as an integrated part of the ITCS. The operator can specify the weather and operating conditions that will be used as inputs for the vessel model. All relevant operating conditions, control modes and different failure modes can be simulated.

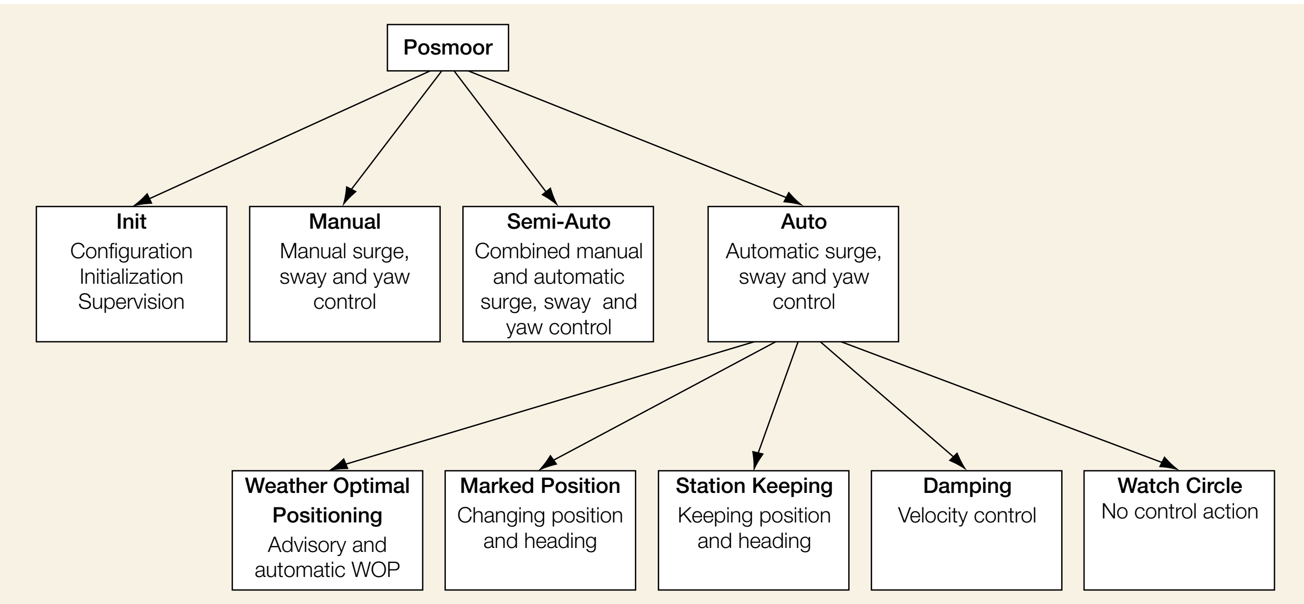
ITCS control architecture

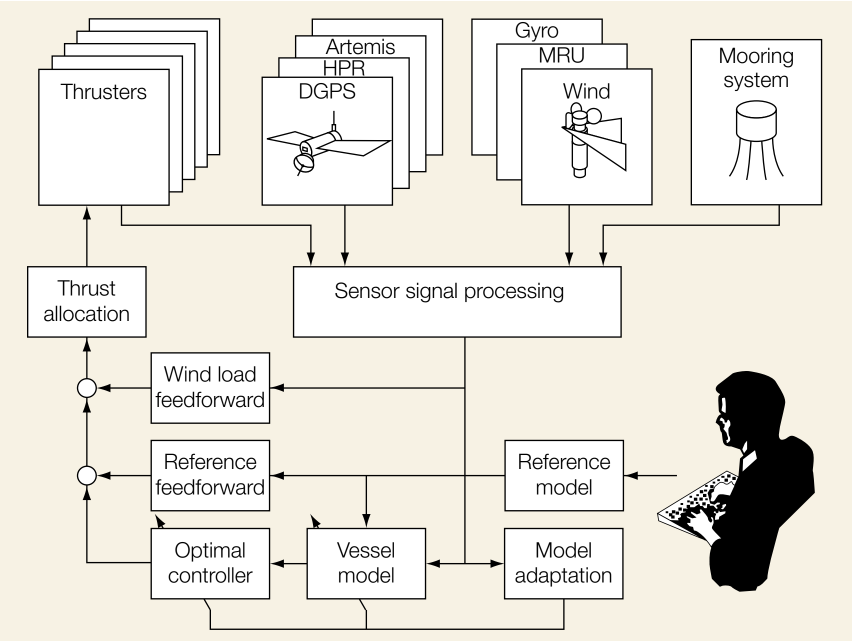
The ITCS control architecture consists of a signal processing module, a non-linear optimal feedback controller, a feedforward controller and a thrust allocation module **7**.

Signal processing

Signals from position reference systems, sensors, thrusters and the mooring system are checked for errors before being accepted and used in the controller algorithms.

Modes and functions of the position mooring system, Posmoor **6**





Architecture of the integrated thruster control system **7**

DGPS *Differential global positioning system*
Gyro *Gyrocompass*
HPR *Hydro-acoustic position reference*
MRU *Motion reference unit*

Each signal is processed with respect to its:

- Range and wild point
- Low and high variance/derivative

Additional tests can be performed for redundant measurements:

- Signal difference (two signals)
- Signal voting (three or more signals)

If there are two or more signals and no errors are found in the signal quality check, a weighted signal based on signal variance calculations is determined and used in the controller algorithms. The operator can choose between manual and automatic weighting.

Vessel model

A mathematical model describing the vessel dynamics is separated into a low-frequency model and a wave-frequency model. The wave-frequency motions are assumed to be caused by first-order wave loads. The low-frequency motions are assumed to be caused by second-order mean and slowly varying wave loads, current loads, wind loads, mooring forces and thruster forces. The controller compensates low-frequency position and heading motions, but not wave-frequency-induced motions.

The filtering of the wave-frequency-induced motion components from the total motion measurements is performed by a non-linear observer in a Kalman filter configuration.

The observer-corrected states are used in the controller algorithms.

If heading and/or position information is lost, the observer-predicted states are used in the controller algorithms, being denoted as 'dead reckoning'.

Model adaptation

The parameters used in the mathematical model of the vessel vary according to the variations in the operating and environmental conditions. The system automatically provides the necessary corrections to the vessel model and controller gains subject to certain changes in the vessel parameters and variations in sea states.

Optimal feedback controller

This multivariable, non-linear controller produces feedback control action based on the estimated low-frequency position and velocity signals from the non-linear observer. The controller is optimized with respect to positioning accuracy, fuel consumption and wear and tear of the propulsion system.

Wind feedforward controller

A wind feedforward controller is used for fast disturbance rejection involving wind loads acting on the vessel.

The wind feedforward can be enabled and disabled individually in surge, sway and yaw.

Wind feedforward requires the wind sensor to be enabled.

Reference model and reference feedforward controller

To ensure high-performance tracking, a feedforward control function based on input from the reference model is added to the control vector.

The reference model generates a smooth trajectory between the previous and the new heading and position set-points. The reference feedforward controller accounts for inertial and damping properties of the vessel.

Line-break detection and feedforward controller

When a line break is detected, a line break feedforward controller in Posmoor is activated which compensates for the lost forces and moment produced by the broken line.

The information used for line-break detection is a sudden drop in the measured tension in an anchor line, followed by increased tension in the neighbouring lines and vessel motion in the direction of the broken line.

When the vessel is controlled in semi-auto or auto mode and a line break is detected, the system automatically shifts to Posmoor 'station-keeping'. The degrees of freedom controlled manually by the operator will remain in manual.

The line-break feedforward is slowly reduced to zero, the feedback controller providing the necessary control. Manual override of the line-break detection function is possible.

Thrust allocation

Using the required forces and moment received from the controller as a basis, the thrust allocation algorithm determines the optimum thrust for each thruster device, as well as the orientation in the case of automatically controlled azimuthing thrusters. The following quantities are minimized: fuel consumption, the difference between the required and the resulting forces and moment, wear and tear of the azimuthing thrusters.

Features of the thrust allocation algorithm are:

- *Flexibility:* the thrust and azimuth angles of the remaining thrusters are optimized in the case of thruster failure or disabling; this applies even when only one thruster remains.
- *Advanced azimuthing control:* the azimuthing thrusters are controlled such that the mean environmental forces and moment are optimally compensated. High-frequency wave disturbances are disregarded, resulting in very fuel-efficient control with high performance and minimal wear and tear. Moreover, for bi-directional thrusters the algorithm allows negative thrust components to avoid frequent 180° turns of the thruster. However, if a thruster applies more negative than positive thrust during a specified time interval the thruster is turned 180° since the thrusters are more efficient in the positive direction.
- *Forbidden zones:* certain azimuthing sectors can be configured as 'forbidden zones' in order to prevent loss of thrust due to thruster-thruster interaction and loss of HPR position accuracy due to noise from the thruster race. The thrusters can, however, pass through these zones on the way towards the optimal direction.
- *Prevention of power blackouts:* if the available power, as specified by the Energy Management System for the propulsion, becomes too low, the thrust is scaled down to prevent an electrical blackout; forces and moment are still applied in the optimal direction.

Total integrated solution

The safety and automation system that monitors and controls the power plant, propulsion, thruster system and process plant is becoming increasingly important to the optimized running of the installations. The need to save costs and achieve a fast payback on investments has led to shorter lead times for the electrical equipment – typically less than one year from order to installation. Less engineering effort is invested in the early design stages than in traditional offshore projects, leaving more engineering work to be carried out in parallel with the detailed design, construction and manufacturing. This new reality presents challenges to owners, yards and suppliers alike, and leaves little room for the classical offshore engineering processes, which are time-consuming and expensive. Because of this, more responsibility for the design and for interfacing the systems is being passed to the yard. However, many yards and operators do not have the infrastructure needed to perform this work, so that more and more of this responsibility is being transferred to the suppliers. The present trend in the market is towards greater system responsibility having to be borne by the vendors of the larger packages **8**.

These changes in the market have been brought about by the mutual interest of all parties in the following:

- Dealing with one contractual partner
- Single system responsibility, thereby reducing the risk taken by the customer during construction, commissioning and operation, and avoiding sub-optimization, mismatch and divergence in interfacing and functionality
- Simplified engineering and installation due to functionality and interfaces being designed to proven product standards
- A single process signal interface and use of fieldbus process I/Os to reduce cabling and lower installation and commissioning costs
- A unified system for reduced maintenance and spare parts inventory
- Higher system integrity
- Safe, ergonomic operation based on a uniform man-machine philosophy for all the systems
- Better overall performance and stability through utilization of the potential offered by functional integration
- Uniform training and documentation
- Financing

The integration of power and automation systems has both a physical and a functional aspect. While the advantages of physical integration are obvious and immediately apparent, the benefits of functional integration are more evident during operation and result in improved safety and control plus a significant reduction in fuel consumption. Examples of functional integration are:

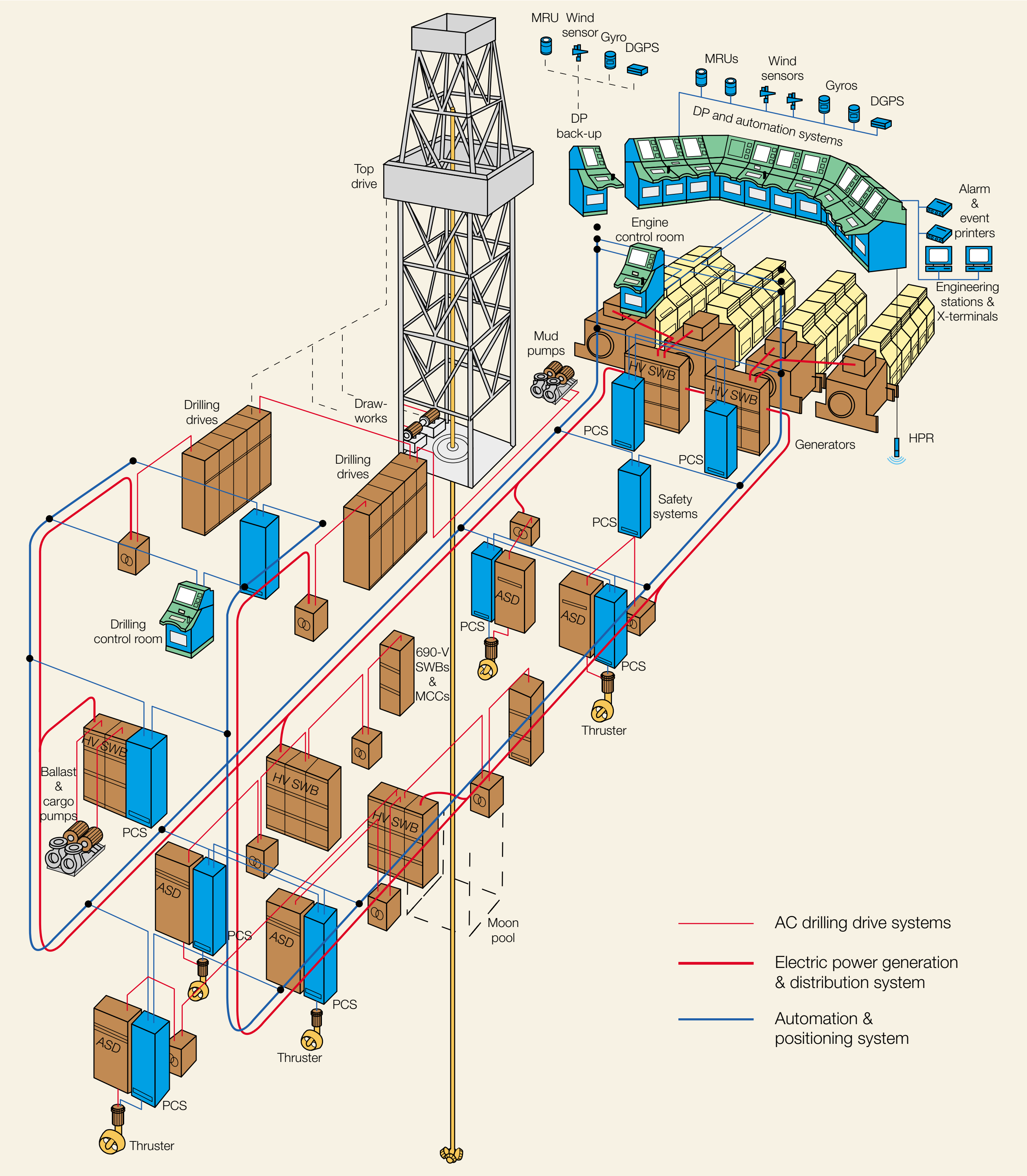
- Intelligent and predictive blackout prevention and active power network stabilization
- Automatic/remote setting and control of intelligent motor starters
- Enabling of a 'sleep' mode for improved operational economy
- Combined power and torque control of thruster drives, etc, for improved dynamic performance of Dynpos and better power network stability

- Advanced condition monitoring and diagnostics, based on the analysis of multiple measurements

Experience based on analyses of power stability and positioning performance achieved with the physically and functionally integrated power and positioning system from ABB has pointed up significant operational and safety advantages over conventional

Total integrated power, automation and positioning system for a drill ship **8**

ASD *Adjustable-speed drive*
DP *Dynamic positioning*
MCC *Motor control center*
PCS *Process control system*
SWB *Switchboard*
Other notation, see Fig. 7

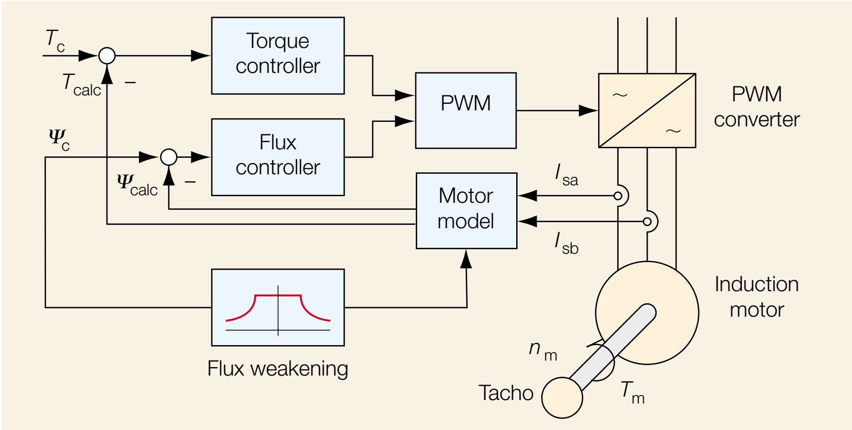


technology. The individual benefits of power and automation technology, combined with extended process knowledge, are fully utilized all the way from design to operational implementation. This is vitally important for safe operation and maximum production/drilling availability.

Advanced thruster control

As mentioned earlier, the positioning systems include control functions for automatic positioning and guidance. The positioning controller computes command signals for the surge and sway forces and the yaw moment, and the thrust allocation algorithm determines the corresponding force and direction each thruster and propeller device must produce in order to carry out these commands. Advanced mathematics based on singular value decomposition and geometrical filtering techniques are used to find the optimal force and direction for each thrust device while avoiding singular thrust behaviour. The result is reduced wear and tear and energy consumption for all thrust configurations and types of thruster. Conventionally, the final thruster pitch or speed set-point signals are determined from stationary propeller force-to-speed/pitch mappings based on the thruster characteristics and information on bollard pull tests provided by the thruster manufacturer. These relationships may later be modified during sea trials. However, the thrust characteristic is strongly affected by the local water flow around the propeller blades, the hull design, operational philosophy, vessel motion, waves and water current. Deviations between these stationary nominal force-to-speed/pitch mappings and the actual situation due to local water flow phenomena are not compensated directly by the control system, resulting in reduced positioning performance in terms of accuracy and response time. In addition, the performance and stability of the electrical power plant network will deteriorate due to unintentional peaks or power drops caused by load fluctuations on the propeller shafts. The unpredictable load variations force the operator to have more power available than is necessary to be sure of preventing blackouts. This implies that the diesel generators will run on average for more hours at lower loads, increasing wear and tear, and therefore the maintenance that is needed. A total integrated electric power, automation and positioning system featuring functional integration turns thrust allocation based on a combination of torque and power control of the propeller and thruster devices into an attractive and feasible solution that overcomes these problems.

The combination of torque and power control means that the thruster allocation by the Dynpos controller converts a thrust de-



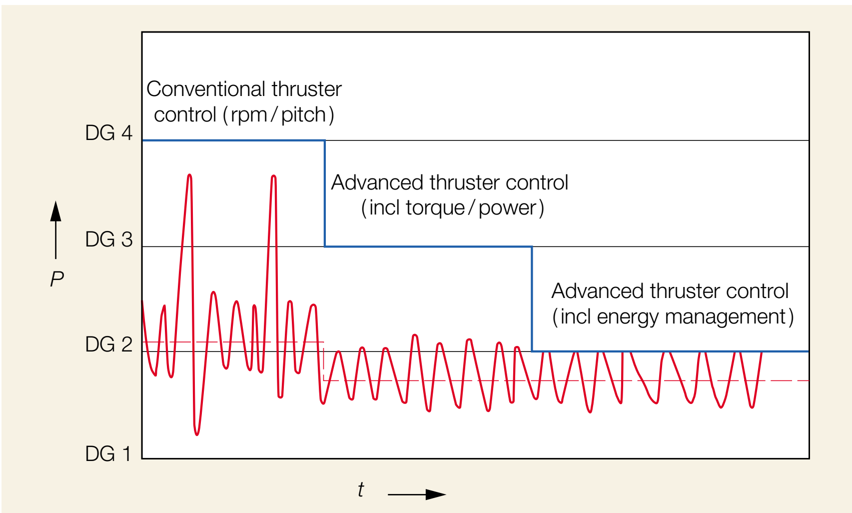
Torque loop in electric motor drive **9**

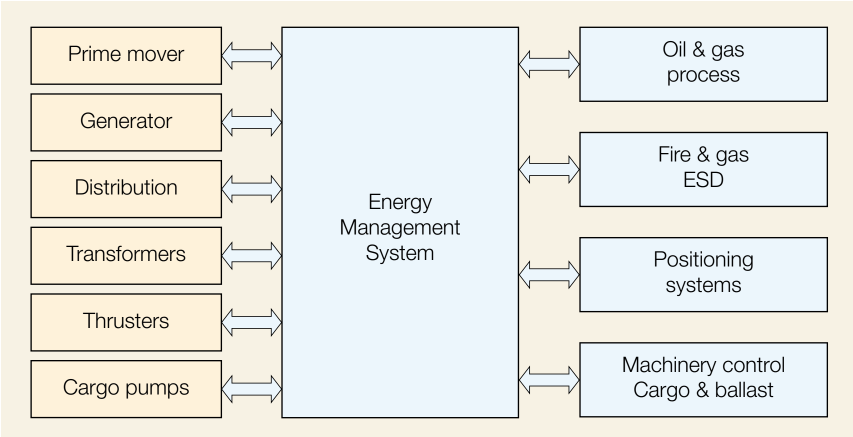
PWM *Pulse-width modulation*

I_{sa} *Stator current, phase A*
I_{sb} *Stator current, phase B*
n_m *Mechanical rotational speed*
T_c *Torque command*
T_{calc} *Calculated (estimated) torque*
T_m *Actual torque*
ψ_c *Flux amplitude command*
ψ_{calc} *Calculated flux amplitude*

Impact of thruster control strategies on power system stability **10**

DG *Diesel-generator set* P *Power* t *Time*





Energy management system 11

ESD *Emergency shutdown system*

mand to a torque/power demand instead of a speed reference. This also has to be reflected in the control configurations of the electric motor drive, where certain modifications have to be made 9.

By applying a combination of torque and power control, the Dynpos system can control the motor shaft power with great accuracy, resulting in smaller power fluctuations in the network and less likelihood of blackouts with reduced spinning reserves. The effect of applying combined power and torque control on the power stability is shown in 10.

Coordinating role of the energy management system

In a system with electric power installations, a vessel and process automation system and a positioning system, the different parts of the automation system control 'their' parts of the power system. The interconnecting point for all the installed power equipment is the power distribution system. Starting and inrush transients, load variations and network disturbances due to harmonics cause the load and generators to interact and influence each other. Optimized operation and control of the power system is essential for safe running with minimum fuel consumption. An Energy Management System (EMS) 11 optimizes the energy balance and fuel consumption by analyzing historical data, monitoring and controlling the actual power generation and distribution, and predicting and planning future power demands.

The main functions of the EMS can be grouped as follows:

- *Power generation management:* overall control with frequency and voltage monitoring (monitoring, and possibly control, of active and passive load sharing) and load-dependent starting and stopping of generator sets. Since control logic and interlocking functions play a significant role in the power system switchboard design, the functionally of these systems must be coordinated.
- *Load management:* load monitoring and coordination of power limiting functions in other systems, load shedding and start interlock of heavy consumers based on available power monitoring.
- *Distribution management:* reconfiguration and sequence control of reconfigurations of the power distribution system. The distribution system should be configured to suit the requirements of the vessel's actual operating mode.

References

[1] T. I. Fossen: Guidance and Control of Ocean Vehicles. John Wiley and Sons Ltd. (1994).

[2] J. P. Strand, A. J. Sørensen, T. I. Fossen: Modelling and control of thruster assisted position mooring systems for ships. 4th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC '97), Brijuni, Croatia, 160–165.

[3] O. J. Sørdalen: Optimal thrust allocation for marine vessels. IFAC J. of Control Engineering Practice, vol 5/97, no 9, 1223–1231.

[4] A. J. Sørensen, S. I. Sagatun, T. I. Fossen: Design of a dynamic positioning system using model-based control. IFAC J. of Control Engineering Practice, vol 4/96, no 3, 359–368.

[5] A. J. Sørensen, A. K. Ådnanes, T. I. Fossen, J. P. Strand: A new method of thruster control in positioning of ships based on power control. 4th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC '97), Brijuni, Croatia, 172–179.

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