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Dynamic Modeling of a Supply Vessel Power System for DP3 Protection System

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Abstract—**The work is focused on modeling and simulation of a supply vessel from a static and dynamic perspective in an integrated way. Modern marine vessels with electric propulsion are becoming more and more complex systems. Therefore, there is a strong necessity to develop models capable to integrate different subsystems in order to evaluate the overall performance under faults conditions, harsh weather and other critical situations. In particular, the focus of the work is to highlight the need to implement zonal protection scheme to respect DP3 (Dynamic Position 3) constraints in case of severe busbar faults, operating the system with the main tie breaker closed.**

The model developed is characterized with a complete representation of a Platform Supply Vessel (PSV). The model represents also the full protection system (static and dynamic) in accordance to fine-tuning conducted on the real system. In this work, the innovative contribution is the investigation of the short-term dynamics after a busbar faults with a detailed electric model of the full network taking into account zonal power system protections and load shedding actions. The work is also focused on representing the electromechanical model of the propulsion power converters.

Index Terms—**Dynamic modeling, DP3, zonal protection, prime mover, short-circuit calculation, load shedding.**

I. Introduction

Nowadays modeling and analysis of marine power systems is gaining higher and higher relevance. There is a need, in fact, to investigate the ship's power system behavior starting from the early design phase. Indeed, ships are isolated power systems in which generation, distribution and loads coexist in a restricted and hostile environment.

The electric energy vector has become even more important for ships where all energetic needs, from propulsion to hotel, are provided through electric power (i.e. All Electric Ships AES). This vision has been particularly successful in applications with restrictive space, comfort and performance constraints such as passenger and offshore supply vessels. Furthermore these vessels present a strong coupling among the different functionalities. Therefore, a strong coordination among the different subsystems is required and suggested [1]-[2]. This, because of its characteristics such as the closeness between loads and generators, the similar size between them and the more and more significant presence of converters. As a result, there is the opportunity to migrate in marine field some technologies developed in the research activities related to smart grids and microgrids [3] and implement energy efficiency management approaches.

Actually, there is the possibility to operate in a coordinated and smart way on generators and loads, in order to save fuel and money [4].

A Dynamic Positioning (DP) system is to be designed to have a certain level of station keeping capability, reliability and redundancy [5]. For a vessel with the notation DP3, a loss of position may not occur in the event of a single fault in any active or static component or system, including complete loss of a compartment due to fire or flood. International Maritime Organization (IMO) defines the conditions of the worst possible scenario [6]. Basically, DP analysis examines the failure mode in the worst possible situation when the remaining thruster engines must be able to maintain the position under the environmental design criteria defined for the class. Furthermore, whichever failure occurs, it will never lose the ability to stay in place, and the project will thus meet the requirements of the IMO DP Class 3 regulations. Essential services for generators and their prime mover, such as cooling water and fuel oil systems are to be arranged so that, in case of a single fault in the systems or the loss of any single compartment, sufficient power remains available to supply the essential loads, the critical operational loads and to maintain position within the specified post failure operating envelope.

According to the International Marine Contractors Association (IMCA), about 10-24% of DP accidents in the period between 2000 and 2009, were caused by errors in the power generation [7]-[8]. Even hard DP2 and DP3 vessels have a high level of redundancy if a single fault in the system is detected and handled correctly; they can spread to the entire bus and can cause loss of the entire system [9] . Introduction of the new DNV class DP DYNPOS ER also opens to the DP2 and DP3 operation with tie closed [10] . In such a system, the proper identification and handling of the fault is essential.

All these reasons motivate the implementation of the model of the power system of a medium size vessel within a software

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environment dedicated to power system analysis [11] in order to perform static and dynamic studies aimed at testing and validating the proposed methodologies. A preliminary work has been presented in [12], where a simpler model has been developed. In [2], [9] an integrated model is developed in order to simulate the full marine dynamics of the shipboard power system with a focus on the mechanical dynamics. In this work, the main contribution is to investigate the short-term dynamics after a busbar faults with a detailed electric model of the full network taking also into account power system protections.

The rest of the paper is organized as follow: Section II reports a description of the ship and environmental model selected, Section III describes the power system model, Section IV introduces protection model implemented, Section V presents the simulation results and Section VII draws some conclusions.

II. Ship, Environment and Thrusters Models in DP3

The reference vessel HAVYARD LEIRVIK NB111/ P201115 model 833 PSV has been characterized in accordance to the data provided by the manufacturer. A side view of the ship is depicted in Fig. 1. Table I reports some technical data of the vessel.

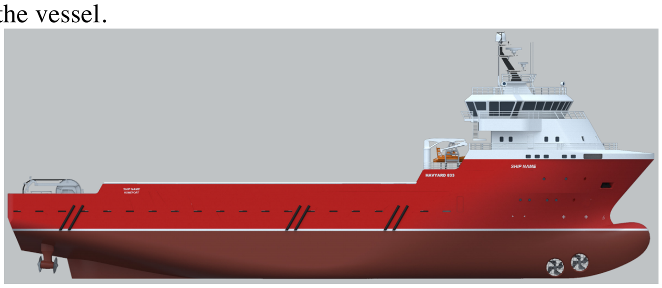

Fig. 1- Havyard Leirvik supply vessels side view

TABLE I
TECHNICAL DATA OF SHIP

Main particulars	
Length overall	86.8 [m]
Length between perpendicular	76.8 [m]
Breadth moulded	19.6 [m]
Maximum draught	6.5 [m]
Main data	
Speed at draught 5.0 m	15 [knots]
Dead weight at draught 6.5 m	4700 [ton]
Generator sets (G 1, G 2, G 3, G 4)	4 x 1900 [kVA]
Main Azimuth thrusters (MP 1, MP 2)	2 x 1900 [kW]
Thrusters forward (BT 1, BT 2)	2 x 880 [kW]
Retractable Azimuth thruster (RT)	800 [kW]
Accommodation	27 persons

The main function of a supply vessel is to serve offshore platforms and offshore wind farm installations. Platform Supply Vessel (PSV) transports supplies (e.g. working materials, personal and provisions) from the operational base to the offshore installations, back and forth. It is usual, for these kind of ships, being able to perform other duties such as fire-fighting (fi/fi) and extinguishing, oil-spill preparedness and installations maintenance. Consequently, PSVs are multitasking ships. Therefore, unlike any other ship, they have to be designed to work in many different operative conditions (i.e. they should cope with different purposes) and scenarios (i.e. weather conditions and operational profiles). Another consequence of being a multi-tasking vessel is that the determination of the best design range with regard to economy of scale (i.e. in terms of size) and economy of scope (i.e. specialization) becomes more challenging [13].

Due to operational and safety reasons, a PSV needs to be able to maintain its position (i.e. position keeping ability), to control the motions (i.e. sea keeping ability) and maneuvering in a seaway condition over longer sustained periods. All these ship control characteristics are included in the Dynamic Positioning (DP) system. The DP system works combining control system (i.e. sensor position reference systems and control), propulsion systems (i.e. thrusters) and electrical systems (i.e. power plant).

In recent years, with the introduction by IMO of new regulations and guidelines for vessels with DP systems this has become no longer an option for new buildings. These ships are configured as DP vessels in class DP1, DP2 or DP3 [10] depending on their ability and safety in station keeping and motion control as shown in Table II.

TABLE II
DP CLASSIFICATION [4]-[14].

DP1	Has no redundancy. Loss of position may occur in the event of a single fault.
DP2	Has redundancy so that no single fault in an active system will cause the system to fail. Loss of position should not occur from a single fault of an active component or system such as generators, thruster, switchboards, remote controlled valves etc. But may occur after failure of a static component such as cables, pipes, manual valves etc.
DP3	Which also has to withstand fire or flood in any one compartment without the system failing. Loss of position should not occur from any single failure including a completely burnt fire sub division or flooded watertight compartment.

Nowadays, DP1 is almost a standard for new builds, instead DP2 and DP3 are reserved in case of higher reliability and special operative scenarios. The higher numbers in classification means greater reliability and safety. This can be achieved through equipment redundancy, higher attention into system fail-safes and isolation of equipment problems without loss of vessel function at critical times.

A. *Proposed Model for DP*

Being the aim of this work to investigate the behavior of the shipboard power systems in case of faults when the ship is working in heavy scenarios, it is essential to develop a model for the dynamic positioning system. Considering electrical and ship dynamics, it is possible to verify that the first ones are faster than the second. Furthermore, environmental dynamics are slower that the ship ones (e.g. typically electrical dynamics are in the order of 1 to 100 milliseconds, the ship ones are in the order of 1 second to 10 minutes for dynamic positioning and, on the other hand, the environmental dynamics are in the order of 1 second to 1 month). In this context, there is no need to consider ship and environmental dynamics in order to study the power system behavior. Nevertheless, there is the need to evaluate, in accordance with the normative [6]-[10]-[14], the worst possible environmental scenario in which the power system should remain in function in case of the worst possible failure occurs. For these reasons, the environmental forces have been calculated in accordance to the normative formulation [10]; which represents a static balance between environmental forces and thruster’s outputs.

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B. Environmental Forces Model

This model assumes coincident wind, current and waves direction (e.g. directed on the beam). For the ship under exam, an Environmental Regularity Number (***ern***) equal to 95 has been chosen in order to identify its DP 3 class capability.

Because of the ***ern*** chosen, the following weather conditions reported in Table III have been selected in order to evaluate the external forces acting on the ship.

TABLE III
ENVIRONMENTAL CONDITIONS [10]

ern	V_{WIND}	V_{SC}	H_S	T_Z
95	17.6 m/s	0.75m/s	4.9 m	9.0 s

Where:
- V_{WIND} Wind speed
- H_S Significant wave height
- T_z Wave period
- V_{SC} Sea current speed

1) Sea Current Forces

Sea current forces have been calculated using the following equations:

$$F_{SC_X} = 0.5 \cdot \rho_{H2O} \cdot C_{SC_X} \cdot A_{SC_X} \cdot V_{SC}^2 \quad (1)$$

$$F_{SC_Y} = 0.5 \cdot \rho_{H2O} \cdot C_{SC_Y} \cdot A_{SC_Y} \cdot V_{SC}^2 \quad (2)$$

$$N_{SC} = 0.5 \cdot \rho_{H2O} \cdot C_{SC_N} \cdot A_{SC_X} \cdot L_{BP} \cdot V_{SC}^2 \quad (3)$$

Where:
- F_{SC_X} Sea Current Force in surge direction (x)
- F_{SC_Y} Sea Current Force in sway direction (y)
- N_{SC} Sea Current Moment of yaw
- ρ_{H_2O} Sea water density
- C_{SC_X} Longitudinal drag coefficient
- C_{SC_Y} Transversal drag coefficient
- C_{SC_N} Yaw drag coefficient
- A_{SC_X} Longitudinal project area below water
- A_{SC_Y} Transversal project area below water
- L_{BP} Length between perpendicular

2) Wind Forces

The Blenderman's method, which is suitable also for PSV ships, has been implemented [15] in order to evaluate the forces due to wind. According to this method, it was possible to calculate the surge and sway forces and the moment of yaw.

3) Wave Forces

This kind of loads have been calculated using the Holtrop and Mennen method [16]-[17]. This is a statistical method used to predict the ship resistance due to wave-making and wave-braking through some assumptions on the geometrical and operative characteristics.

4) Wave Drift Forces

This is calculated for beam waves with the following equation (4) [14].

$$F_{DRIFT-WAVE} = \int_{\omega=0}^{\infty} 2S(\omega)ARO(\omega)d\omega \quad (4)$$

Where:
- $F_{DRIFT-WAVE}$ Wave drift forces
- $S(\omega)$ Wave spectrum
- $ARO(\omega)$ Amplitude response operator

C. Propeller Models

Thrusters have been modeled as propellers driven by electrical motors. These propellers are assumed to be Fixed Pitch Propellers (FPP). This because of the nature of this study, as previously reported, where the simulations dynamics are short enough to allow static assumption for what concern the ship and environmental models.

1) Propellers Design

Considering the environmental conditions as a static situation it is possible to design each propeller with the following assumptions [18]:
- The diameter **D** of each propeller is known a priori.
- The total resistance $\mathbf{R_T}$ of the ship is known (i.e. calculated by using the Holtrop and Mennen method [16]).
- The relative speed of the ship $\mathbf{V_R}$ is calculated as the vectorial product between the current and wave velocity.
- The advanced speed $\mathbf{V_A}$ is chosen to be equal to the relative ship speed $\mathbf{V_R}$ (i.e. no iteration between hull-propellers or wave-propeller has been included).

With the previous assumptions, it was possible to proceed to design each propeller starting from the knowledge of the diameter [19]. Once the propellers are designed, it is possible to calculate the thrust (**T**) in function of their speed (**n**) and thrust factor (K_T) with the following equation:

$$T(n) = sign(n)K_T\rho_{H2O}D^4n^2 \quad (5)$$

2) Thrusters Allocation

Usually the thruster allocation system is used in dynamic simulations as a controller in order to evaluate the thrust required by each propeller aimed to guarantee the total thrust [20]. In this work the total thrust required by the ship is a constant signal. Therefore, the results of the thruster allocation system are:
- The thrust configuration matrix **T**.
- The thrust orientation matrix (i.e. for Azimuth propellers) $\boldsymbol{\alpha}$.
- The diagonal matrix thrust force coefficients **K**.
- The propeller speed vector $\mathbf{u_C}$.
- The thrust required by each propeller matrix $\boldsymbol{\tau}$.

With the following formula, it was possible to calculate the thrust required, revolution speed and orientation of each propeller [21].

$$\tau = T_{3\times r}(\alpha)Ku_C \quad (6)$$

Using the open water characteristics for each propeller it is then evaluable the propellers speed and torque, which are useful parameters to perform the electrical system simulations.

III. POWER SYSTEM MODEL

Electric power plant is composed by seven main busbar connected by tie breakers and transformers enabling different configuration for supplying load busbars. Voltage levels are 690 V at generation and motors busbars and 440 V and 230 V for the load busbars. Grid frequency is 60 Hz.

As it is shown in Fig. 2, four diesel generators, with nominal electric power equal to 1900 kVA each, compose the generation plant. Inverter driven asynchronous machines compose the main propulsion and thruster motor set. Nominal power is 1900 kW for the two propulsion motors, 880 kW for the two bow thrusters and 800 kW for the retractable thruster.

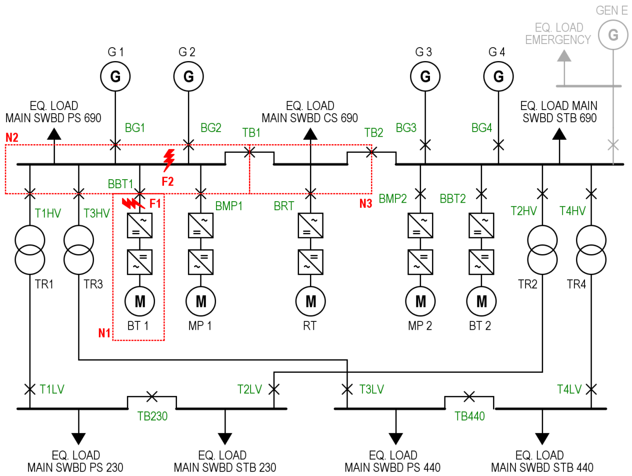

Fig. 2 - Shipboard Power System Scheme

Table IV shows the result of the Electrical Power Load Analysis (EPLA). Through the EPLA, it is possible to determine the amount of electrical power required in different ship's operative scenarios [21]. Being the aim of this work to study the electrical system behavior in DP scenario, in Table IV only this condition has been reported taking into account the utilization factor (**F**$_U$) and the contemporaneity factor (**F**$_C$) for the different loads. **F1** and **F2** represent the load status after faults events (case 1 and case 2 simulation scenario reported in Section V).

Static and dynamic models of all the equipment have been implemented in order to describe the behavior of electromechanical components and controllers. Devices have been modeled according to the dynamic parameters available from manufacturer and from literature [23]-[28].

A. *Control System Architecture*

The implemented control system architecture considers the most significant functionalities of Power Management System (PMS) and Dynamic Positioning System (DPS).

The PMS controls the power system in order to maximize vessel performance, while meeting blackout prevention and fuel consumption requirements [27].

Active and reactive power dispatching, propulsion load limiting and black out prevention are the main tasks. For the purpose of this work, the proposed system architecture considers the following functionalities:

- *Active power sharing*: the frequency control signals distribute the total amount of active power production equally to the available generators.
- *Reactive power sharing:* ensure the voltage level at the main switchboard busbar, sharing the reactive power production equally to the available generators.

Fig. 3 shows the implemented logical scheme for each generator set. Secondary regulation dispatch the total active and reactive power production, defining the references for the primary regulators of each Synchronous Machine (SYM). Frequency control feeds the Prime Mover's (PM) governor through a signal, which control the intake of fuel and the mechanical power. Voltage controller generates the excitation voltage signal.

TABLE IV
ELECTRICAL POWER LOAD ANALYSIS IN DP SCENARIO

Load	**P$_{NOM}$ [kW]**	**F$_U$**	**F$_C$**	**P$_{ACTUAL}$ [kW]**	**F 1**	**F 2**
PROPULSION						
Main Propulsion 1	1900	1	1	1900	On	On
Main Propulsion 2	1900	1	1	1900	On	On
Bow Thruster 1	880	1	1	880	Off	Off
Bow Thruster 2	880	1	1	880	On	On
Retractable Thruster	800	1	1	800	On	On
Aux. Propulsion	73,1	1	1	73,1	On	On
TOTAL POWER ABSORBED [kW] =				6433,1		
HYDRAULIC CIRCUITS						
Starting Compressor	57	0,8	1	45,6	On	On
HPU 1	127	0,8	1	101,6	On	On
HPU 2	127	0,8	1	101,6	On	On
HPU 3	127	0,8	0	0	Off	Off
Aux. to Azimuth	184	0,8	1	147,2	On	On
TOTAL POWER ABSORBED [kW] =				396		
SUPPLY						
Crane 1	25	0,8	1	20	On	On
Crane 2	50	0,8	0	0	Off	Off
Winch 1	26	0,8	1	20,8	On	On
Winch 2	40	0,8	0	0	Off	Off
Hot Water Boiler	410	0,8	1	328	On	Off
Hot Water Boiler	410	0,8	1	328	On	Off
TOTAL POWER ABSORBED [kW] =				696,8		
SERVICES						
Air Conditioning	85,6	0,4	1	34,24	On	On
Steam Humidifier	43,5	0,4	1	17,4	On	On
Defroster	16,3	0,9	1	14,67	On	On
Refrigerator	7,4	0,6	1	4,44	On	On
Ballast Pump 1	84	1	1	84	On	On
Ballast Pump 2	84	1	1	84	On	On
Working air compressor	14,3	0,4	1	5,72	On	On
Catalyze air compressor	14,3	0,4	1	5,72	On	On
TOTAL POWER ABSORBED [kW] =				250,19		
TOTAL POWER ABSORBED IN DP SCENARIO[kW] =				**7776**		

The DPS controls the thruster drives in order to obtain the position keeping of the vessel. The various DP vendors may differ in design methods. However, the basic DP functionalities are signals processing, vessel observer, controller and thrust allocation.

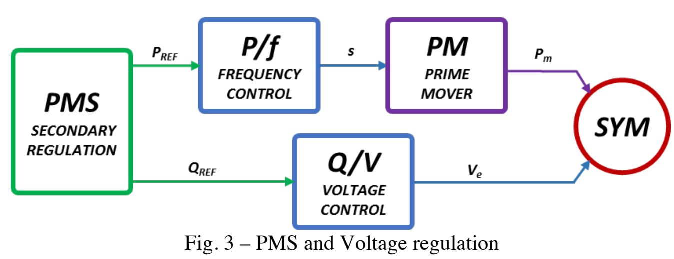

Fig. 3 – PMS and Voltage regulation

For the purpose of this work, the proposed system architecture considers the thrust allocation task, which

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computes the corresponding force command to each thrust device. The thrust allocation module receives updated inputs from the PMS about the total available power and the status of generators [9].

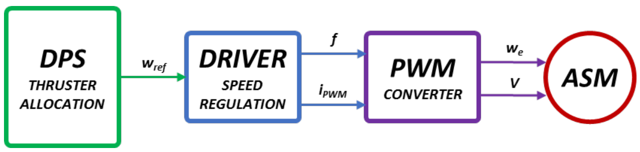

Fig. 4 – DP model

B. *Diesel Generator Sets*

The power generators mainly used in marine application are diesel engines. Each generator set model implements the differential equations that rule the dynamic behavior of synchronous machine, prime mover and regulators.

1) *Synchronous Machine*

A full electro mechanical model for RMS simulations (stator flux transients neglected), models the synchronous machine. Parameters are set according to the manufacturer technical data-sheet.

2) *Automatic Voltage Regulator (AVR)*

Voltage regulator represents one of the key issue for properly model the first transient following a fault. AVR performances affect shape and pick value of the fault current at the generation busbars, which depends to the capability in supporting voltage transient at the generation busbar, i.e. to synchronous machine parameters and voltage regulator settings. The IEEE type 1 AVR has been implemented and parameters have been tuned in order to fit the transient curves provided by the manufacturer in case of fault at the generation busbars.

3) *Primary Frequency Control and prime mover*

Diesel generators belong to the class of reciprocating engines, which use pistons to convert pressure into a rotating motion. The four main generator set models catch the most significant dynamic behavior of the reciprocating engines. Many methods are proposed for modeling the reciprocating generators [18],[20],[23].

The general structure of the fuel actuator system is usually represented as a first order phase lag network, which is characterized by gain and time constant. Fuel flow is converted into mechanical torque by the engine after a time delay and constant torque. The governor controls the speed of the engine by regulating the intake of the fuel.

Several types of governors exist such as mechanical-hydraulic, direct mechanical, electro-hydraulic, electronic, and microprocessor based. An additional control signal is further included in the model, in order to allow the active power sharing (Fig. 5).

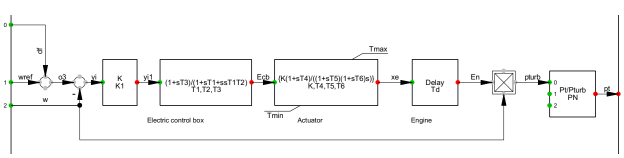

Fig. 5 – Primary Frequency Control and Prime Mover

C. *Main Propulsion and Thruster*

The main propulsion and thrusters models implement the differential equations that rule the electromechanical behavior of inverter driven asynchronous motors.

1) *Induction Machine and Drive Control*

Asynchronous machines have been modelled using a complete electromechanical model (stator transients neglected), coupled with a mechanical load model representing the propeller characteristic.

A breaking resistor equips each drive, allowing severe deceleration of the motor in case of fault condition. A scalar control (V/Hz) has been implemented to control the propulsion motors speed as depicted in Fig. 6.

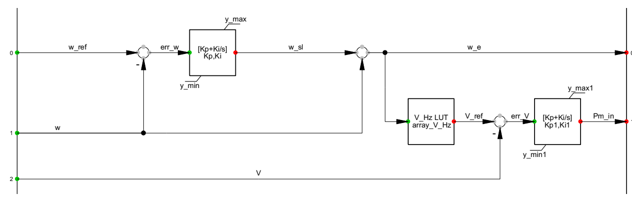

Fig. 6 – Propulsion Motor Speed Control

2) *PWM Converter*

Since the focus of the work is to correctly describe the transient in the first few seconds after a perturbation, a usual phasor model for converter has been adopted [11], [30], [31].

At fundamental frequency, the ideal, loss-less converter can be modeled by a DC-voltage controlled AC-voltage source conserving active power between AC and DC-side.

The implemented control variables are the magnitude of the pulse-width modulation index and the frequency of the output voltage. This is especially useful in variable speed-drive applications, in which a PWM-converter is used for driving an induction machine like in this case.

IV. Protection System Model

Protection devices have been modeled according to the characteristics of real relays and breakers installed on board. Static and dynamic protection models complete the simulation platform, enabling the fault condition studies [31]-[34].

A. *Static Model*

Static short circuit analysis allows the validation of breaker sizing and coordination of protection system. Software can compute fault contributions flowing into each protection device, evaluating the corresponding intervention time.

According to protection data sheets, a combination of three basic time-current curves defines the intervention characteristic of relays:

- Overload (L) – Parameters I_1 and t_1 identify the intervention curve, by editing the overcurrent threshold and the tripping time of protection at $3I_1$, respectively. The time-current characteristic is defined by the so called inverse time equation $I^2t = k$.
- Selective (S) – Parameters I_2 and t_2 identify the current threshold and the intervention delay. The time-current characteristic is defined by the equation $t = k$.
- Instantaneous (I) – Parameter I_3 sets the intervention current. Tripping time t_3 is defined by the manufacturer, as the shortest pick-up time of the device.

Fig. 7 shows the ideal time-current characteristic of the

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protection relays and the described parameters.

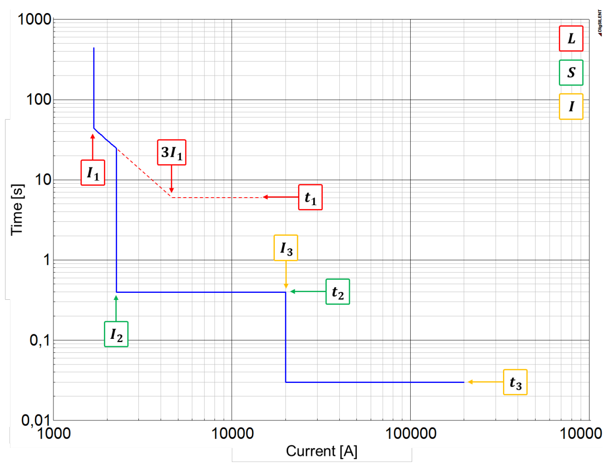

Fig. 7 – Time-Current Characteristic of Protection Relay

B. Dynamic Model

Dynamic models of protection devices give access to the electromechanical transient studies, over all the fault condition scenarios. Dedicated models have been implemented, according to the real technical characteristics previously introduced.

Fig. 8 shows the logic flowchart adopted for the relay modeling. Trip signal represents the protection status i.e. the signal command to the breaker actuator.

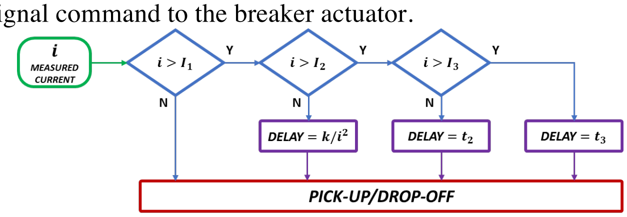

Fig. 8 – Relay Model Flowchart

According to the proposed scheme, pick-up/drop-off block changes the relay status in accordance with the following rules:

- Internal state (trip) changes from 0 to 1 if $i < I_1$ for at least *delay*
- Internal state (trip) changes from 1 to 0 if $i > I_1$ for at least 0 s

Opening time of breaker and tripping tolerances implementation complete the protection modeling, taking into account the behavior of real components. An instance of the proposed model has been implemented for each protection installed, according to the real set-up of devices.

C. Node Protection Coordination

Time-current characteristic of the considered relay models allows the chronometric selectivity implementation. Furthermore, data exchange between protection devices, enable the logical coordination of system.

Zonal selectivity philosophy aims to isolate a fault area delimited by two breakers. Taking the concept to the extreme, a nodal selectivity can be achieved, reducing the zone to the minimum set of detachable equipment.

Nodal selectivity philosophy consists in the coordination of the boundary breakers, which identifies logical nodes. If short-circuit current contributions appear to flow from outside to inside the node, boundary breakers have to open simultaneously. If fault contributions appear to transit the node, boundary breakers have to wait the fault node intervention.

V. SIMULATIONS

The proposed methodology allows evaluating the performances of protection system and the faults effects on the entire power system [12]. The aims of the simulations are the logical selectivity method validation and the evaluation of the short circuit effects in terms of propellers speed and power deviations, in DP operative condition. In fact, in [13] it is stated that the fault verification should be based on calculations and dynamic simulations of the power system in normal operation and during all relevant failure conditions.

Fig. 2 shows the scheme of shipboard power system, in which F1 and F2 indicates the faults location, corresponding to the two proposed case studies. N1, N2 and N3 indicate three logical nodes, involved in the proposed scenarios.

Table V reports the list of acronyms used.

TABLE V
LIST OF ACRONYMS

MAIN SWBD	Main Switchboard	**MP**	Main Propulsion
PS	Port Side	**BT**	Bow Thruster
CS	Central Side	**RT**	Retractable Thruster
STB	Starboard Side	**EQ LOAD**	Equivalent Load

In normal operative conditions (no fault), thruster allocation module (see section II-C2) computes the following speed references for main propulsions and thrusters. Power absorptions depends on the mechanical load applied to each motor.

TABLE VI
SPEED DEMANDS

MP 1	**BT 1**	**RT**	**BT 2**	**MP 2**
0.89 p.u.	0.97 p.u.	0.78 p.u.	0.97 p.u.	0.89 p.u.

A. Case Study 1 – Fault 1

A three-phase short circuit with a 0.02 Ohm purely resistive fault impedance have been simulated at the starting bus of the Bow Thruster 1 line (fault-F1).

Fig. 9 reports the time-current diagram and the fault contributions detected by relays.

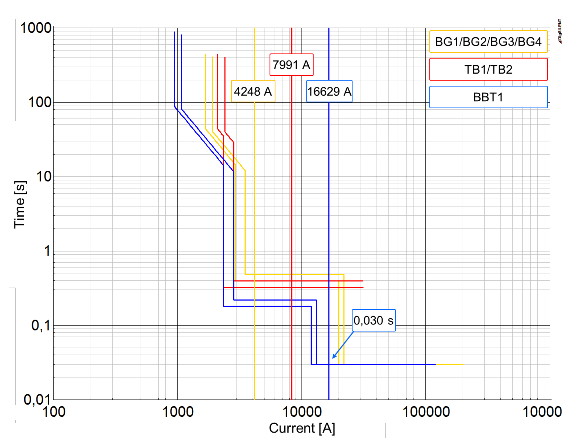

Fig. 9 – Time-Current Plot – Fault 1

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Relay of breaker BBT 1 presents the higher fault contribution and the minimum tripping time, corresponding to the instantaneous intervention curve.

Therefore, chronometric selectivity appears to be effectiveness in coordinating the fault-F1 intervention. Short-circuit determines the Bow Thruster 1 (BT 1) disconnection.

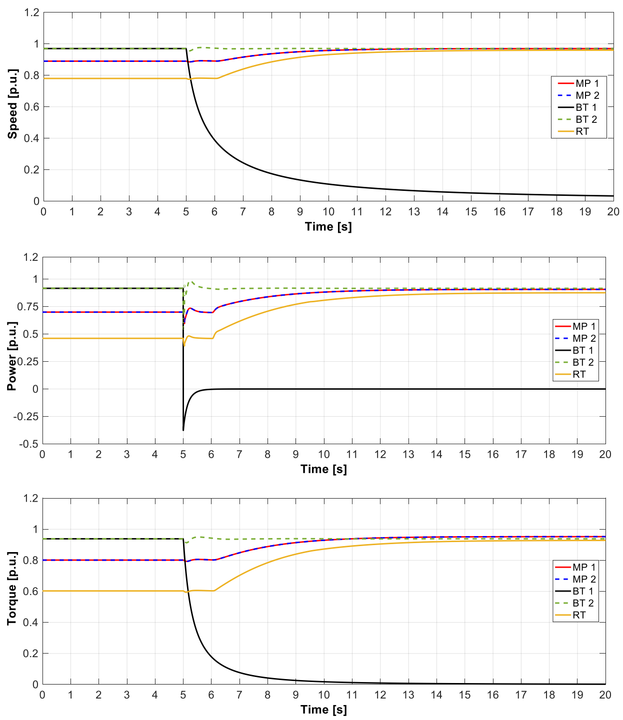

Fig. 10 - Propulsion speed, Power and Torque Transients - Fault 1

The thruster allocation module computes post fault conditions, considering the unavailability of one asynchronous motor.

Table VII reports the new speed references generated for the active thrust devices.

TABLE VII
SPEED DEMANDS

MP 1	BT 1	RT	BT 2	MP 2
0.97 p.u.	OUT	0.96. p.u.	0.97 p.u.	0.97 p.u.

Fig. 10 shows the speed and active power transients for all propulsion motors. Fault occurs after 5 seconds and it is possible to see the dynamic effects of short circuit and breaker intervention.

Generation power reserve can cover the new thrust demands and break-down resistor of Bow Thruster 1 (BT 1) dissipates the energy produced by the severe deceleration of the motor.

Fig. 10 shows motor torques and speeds and the ability of the system to reach the new speed set-point updated by PMS after 1 sec respecting DP 3 scenario.

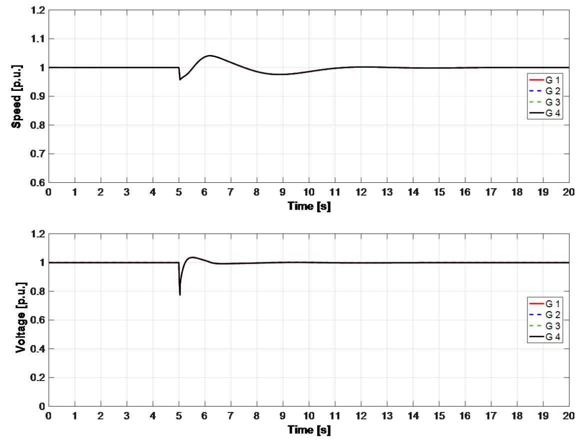

Fig. 11 - Speed and Voltage behavior for generators G 1 - G 4

In Fig. 11 generator speeds and voltages are depicted under this fault condition.

B. *Case Study 2 – Fault 2*

As shown in [13], DYNPOS-AUTRO and DPS 3 based on closed bus-ties need special considerations. For operation with closed bus-ties the power system shall be arranged with bus-tie breakers to separate automatically upon failures, ensuring integrity level comparable to a system based on open bus-ties.

The simulations of the protection system, here reported, is focused on a three-phase short circuit located at the *port side* busbar of the plant: the Main Switch Board Port Side (MAIN SWBD PS 690). Fault impedance is equal to 0.02 Ohm purely resistive and the fault occurs at 5 second past the simulation start.

Fig. 12 shows the time-current diagram and the fault contributions detected by relays. TB1 e TB2 relays tripping time are the same and the chronometric selectivity can fail, causing the loosing of Main Switch Board Central Side (MAIN SWBD CS 690), i.e. the loosing of the Retractable Thruster (RT).

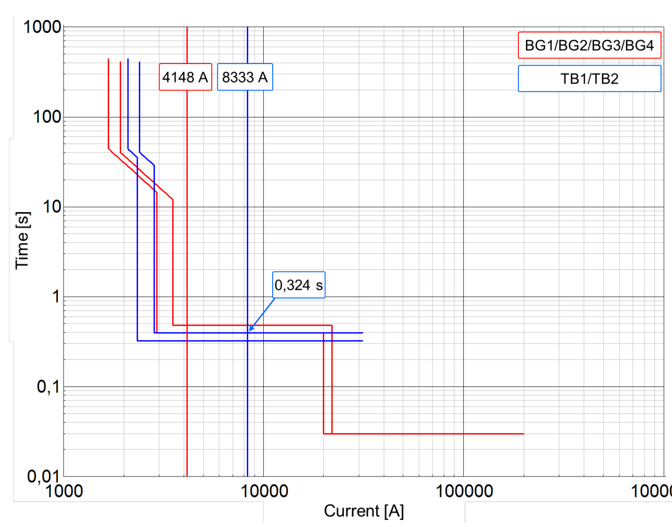

Fig. 12 – Time-Current Plot – Fault 2

Node protection coordination is here required, in order to save a critical portion of power plant. Boundary breakers of node N3 detect that fault is outside the node and define the so-

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called locked ring, inhibiting the TB2 intervention. Boundary breakers of node N1 detect the presence of the fault inside the node and open simultaneously isolating the busbar affected by fault.

Fault effect is the disconnection of motors MP 1, BT 1, and generators G 1, G 2. Thruster allocation module computes the new speed references for the available motors. Due to the generation lack, the power reserve is not enough for achieving the new speed requirements. PMS limits the power absorptions of thrusters within the total generation capacity, pursuing black out prevention implementing load shedding actions (see Table IV - column F2). Table VII reports the ideal speed references and the obtained ones (highlighted).

TABLE VIII
SPEED DEMANDS

MP 1	BT 1	RT	BT 2	MP 2
OUT	OUT	1.15 p.u.	1.10 p.u.	1.11 p.u.
OUT.	OUT	0.90 p.u.	0.97 p.u.	1.01 p.u.

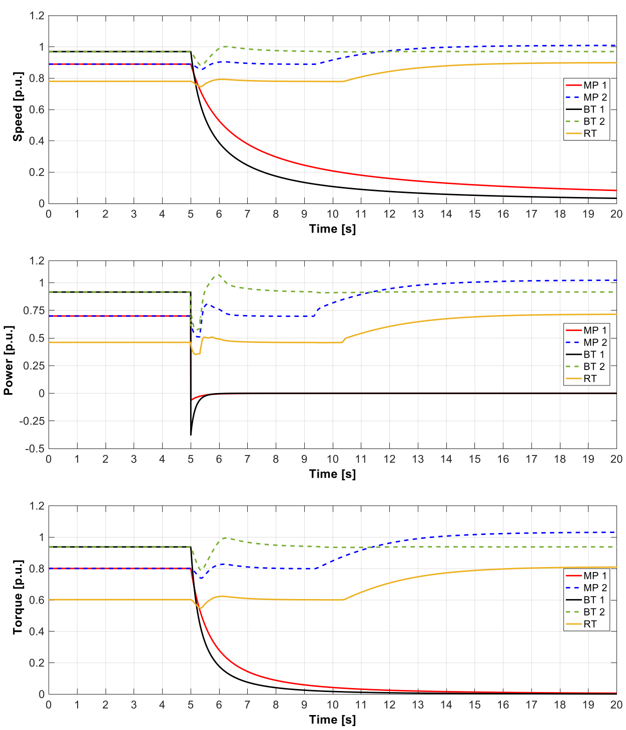

Fig. 13 – Propulsion Speed and Power Transients – Fault 2

Fig. 13 shows the propulsion speed and power transients of the propulsion devices. The limiting action of PMS is also visible in the first transient effects.

Dynamic simulation allows evaluating the electrical and mechanical solicitations of all the machines connected to the grid.

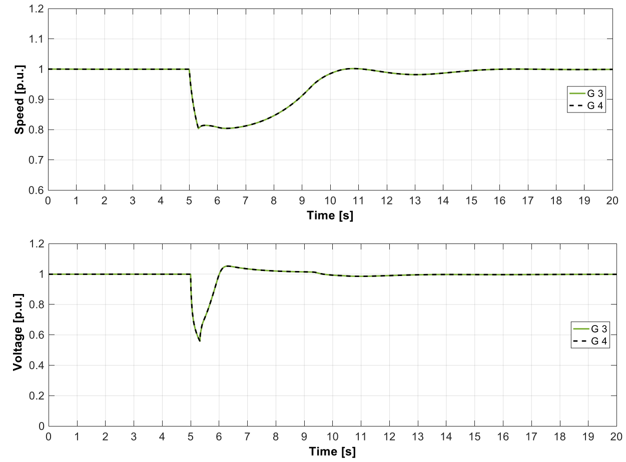

Fig. 14 – Generator Frequency and Voltage Transients

This kind of studies makes possible to appreciate the consequences of the fault in term of electrical stability and mechanical stresses.

Fig. 14 reports the frequency and voltage transient of generator G 3 and G 4.

VI. CONCLUSIONS

The paper has presented a dynamic model of a vessel with diesel-electric propulsion, operating in dynamic positioning. DP is a quite reasonable mature technology and the current trend is devoted to improve fuel efficiency, lifetime of the equipment and to operate safer and safer in the most difficult conditions. Therefore, the introduction of the new DNV class DP DYNPOS ER also opens to the DP2 and DP3 operation with tie closed, operating diesel gensets in parallel with better efficiency and performance. This asks in such a configuration, the proper identification of busbar fault and correct handling thought zonal protection. The simulations clearly demonstrated the necessity to investigate the short-term dynamics after a busbar faults with a detailed electric model of the full network taking into account zonal power system protections and load shedding actions in order to guarantee DP3 operation. The shipboard power system represents more and more a very complex model that requires an integrated model of the different functionalities to better capture the real dynamic of the full system.

APPENDIX

TABLE IX
DRIVE CONTROL PARAMETERS

Name	description	value	unit
Kp	Slip controller proportional gain	0.1	p.u.
Ki	Slip controller integral gain	0.1	p.u.
Kp1	Voltage controller proportional gain	1.	p.u.
Ki1	Voltage controller integral gain	1.	p.u.
ymin	Slip controller minimum output	0.001	p.u.
ymin1	Voltage controller minimum output	-1.	p.u.
ymax	Slip controller maximum output	1.	p.u.
ymax1	Voltage controller maximum output	1	p.u.

TABLE X
PRIMARY FREQUENCY AND PRIME MOVER PARAMETERS

name	description	value	unit
T1	Electric control box time constant	0.2	s
T2	Electric control box time constant	0.1	s
T3	Electric control box time constant	0.5	s
Td	Engine delay	0.01	s
K	Actuator Gain	15.	p.u.
T4	Actuator time constant	1.	s
T5	Actuator time constant	0.1	s
T6	Actuator time constant	0.2	s
K1	Frequency proportional gain	0.05	p.u.
Tmin	Actuator minimum output	0.	p.u.
Tmax	Actuator maximum output	1.1	p.u.

TABLE XI
AVR PARAMETERS FROM IEEE TYPE 1

name	description	value	unit
Tr	Measurement delay	0.02	s
Ka	Controller gain	1	p.u.
Ta	Controller time constant	0.03	s
Ke	Exciter time constant	1.	p.u.
Te	Exciter time constant	0.2	s
Kf	Stabilization path gain	0.05	p.u.
Tf	Stabilization path time constant	1.5	s
E1	Saturation factor	3.9	p.u.
Se1	Saturation factor	0.1	p.u.
E2	Saturation factor	5.2	p.u.
Se2	Saturation factor	0.5	p.u.
Vmin	Controller output minimum	-10.	p.u.
Vmax	Controller output maximum	10.	p.u.

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