Return to Session Directory

DYNAMIC POSITIONING CONFERENCE

October 17-18, 2006

Control

Power Optimal Thruster Allocation

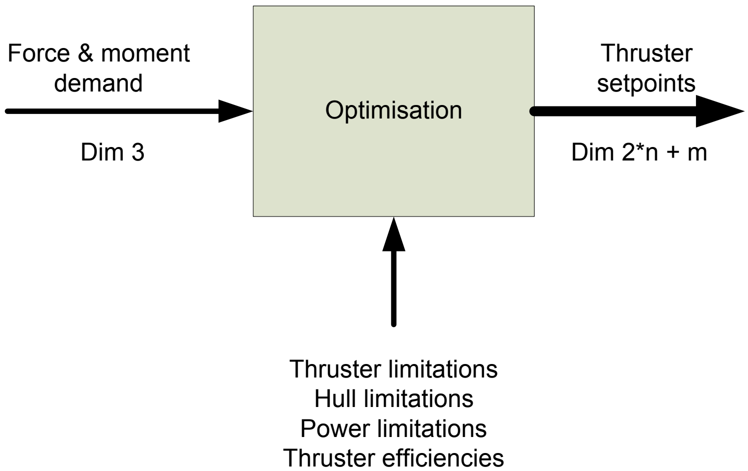
Nils Albert Jenssen and Bjørnar Realfsen

Kongsberg Maritime AS

Kongsberg, Norway

Introduction

The thruster allocation is a complex mapping from a demanded force and turning moment to a set of thruster pitch/ rpm and azimuth setpoints. Since the number of degrees of freedom of thruster controls is normally very high, there exist many such mappings.



In addition the mapping must handle thruster limitations in terms of max and/or min values, permissible azimuth sectors and available switchboard power. The algorithms should also take into account the efficiency of each thruster. This is of special importance for azimuth thrusters which may have degraded efficiency within certain sectors.

The clue is to design the most optimal mapping in some sense. In this paper the power aspects are dealt with.

Mathematical Optimisation

Basic Optimisation Problem

The basic mapping may be expressed as:

> *Minimize the total squared thrust used in order to fulfil the thrust demand given longitudinal and lateral and the rotational moment demand.*

This optimisation task may be formulated as a least squares problem with three demand constraints (equality constraints). The problem can be transformed into a Lagrange relaxed problem, where the objectives function is augmented by the constraints.

A vessel may have thrusters that have a fixed force direction, and thrusters that can rotate the force direction. The vector with optimization variables will have one variable for fixed thrusters. Azimuth thrusters will have two variables. Let us first forget about thruster and power limitations to get an understanding for how optimisation may be used. For simplicity of reading the notation is somewhat simplified.

The objective in the optimisation problem is to minimize the squared thrust used;

$$g_0(t) = \frac{1}{2} \cdot \left(\sum_j w_j \cdot (t_j)^2 \right)$$, where t_j is the thrust of each thruster

The weights, w_j, may be set in several ways, but principally they should reflect each thrusters capability such as e.g. the inverse of the maximum thrust the thruster can provide. In this way we scale the variables so that they will thrust uniformly with respect to percentage of the maximum thrust.

We have three equality constraints in the problem, one for each degree of freedom. The first constraint states that the allocated longitudinal force must be equal to the demanded longitudinal force, d_1:

$$g_1(t) = \sum_j t_j \cdot \cos(\alpha_j) - d_1 = 0$$, where α_j is the thruster azimuth angle

Similarly for the lateral direction

$$g_2(t) = \sum_j t_j \cdot \sin(\alpha_j) - d_2 = 0$$

and finally for the rotational moment

$$g_3(t) = \sum_j t_j \cdot \left(\sin(\alpha_j) \cdot p_j^y - \cos(\alpha_j) \cdot p_j^x \right) - d_3 = 0$$, where p_j^y and p_j^x are the thrusters moment arms

We can now formulate the Lagrangian:

$$L(t, \lambda) = g_0(t) + \sum_{i=1}^{3} \lambda_i \cdot g_i(t),$$

By minimising, $L(t, \lambda)$ in stead of $g_0(t)$ we can solve equality constrained optimisation task simply by solving

$$\frac{\partial L(t, \lambda)}{\partial t_j} = w_j \cdot t_j + \lambda_1 \cdot \cos(\alpha_j) + \lambda_2 \cdot \sin(\alpha_j) + \lambda_3 \left(\sin(\alpha_j) \cdot p_j^y - \cos(\alpha_j) \cdot p_j^x \right) = 0$$

and

$$\frac{\partial L(t, \lambda)}{\partial \lambda_i} = g_i(t) = 0$$

Altogether this will result in a system of linear equations of the form

$Ax = b$, where x contains all unknowns t_j and λ_i.

Thruster Constraints

In addition to these equality constraints we have inequality constraints which may be active or not; upper and lower thruster

These may be formulated mathematically in the following way:

Thruster limitations:

$T_j^{\min} \le t_j \le T_j^{\max}$ where $T_j^{\min}, T_j^{\max}$ are the lower and upper bounds of each thruster

To solve optimisation problems with inequality constraints generally requires a quite complicated iteration process. These iterations are normally imbedded in the numerical procedures, like e.g. standard QP solvers. This will not be handled in this paper.

Any thruster allocation scheme must be able to handle these kinds of constraints.

Power Constraints

Power limitations:

$\sum_j p_j \le P^{\max}$, where $p_j \propto t_j^{\beta}$ is the power consumption of the thrusters (typical β = 1.5) and $P_i^{\max}$ is the max power for each switchboard.

Handling Power Limitations

Power Phase Back

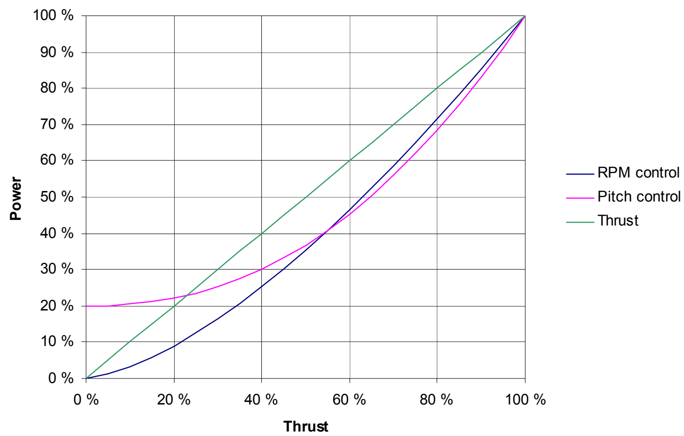
Traditionally power limitations have been handled as a post processing, i.e. power phase back, either by a separate external system such as Power Management or internally in the thruster allocation scheme.

Phase back may be done in several ways:

- Percentage wise distribution of phase back power according to the rated power of each thruster
- Sequenced phase back where least efficient thrusters or pair of thrusters are reduced first.
- Weighted reduction according to thruster efficiency

Often phase back will take place in conditions with insufficient thrust. Normally heading priority will therefore be active. Thruster efficiency may hence often be associated with the moment arm of the thruster. In other cases thrust – hull interactions may be dominant.

It is worthwhile noting, however, that due to the nonlinear relation between thrust and power $p_j \propto t_j^{\beta}$ the percentage wise best utilisation of power (to provide additional thrust) takes place at the lower thrust levels (see figure to the right), which is in favour of the first method. In the following, the approach of using moment arms as a measure of efficiency is studied in more details, $1/|A_i|^m$ Another measure would be thruster – hull reduction, r^n, or the combination of the two, $r^n/|A_i|^m$.



Power versus thrust

Percentage phase back

Assume the power consumption has to be reduced by ΔP. Hence per thruster

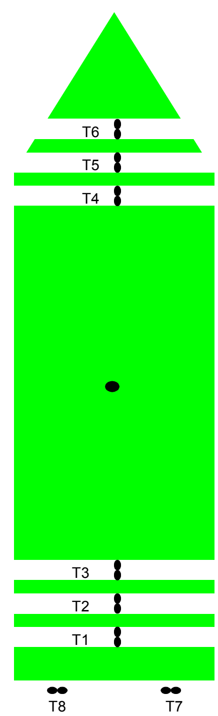
$$\Delta p_i = \frac{\Delta P \cdot (p_i - p_i^0)}{\sum_j (p_j - p_j^0)}$$, i.e. reduction proportional to allocated power above idle (zero pitch) power consumption p_j^0

Arm weighted phase back

Similarly for arm weighting

$$\Delta p_i = \frac{\Delta P \cdot (p_i - p_i^0)}{\sum_j (p_j - p_j^0)} \cdot \frac{1/|A_i|^m}{\sum_j 1/|A_j|^m}$$ where A_i is the resulting moment arm of the thruster

Comparing the two methods for a ship with tunnel thrusters (see figure to the right) shows a certain advantage to the weighted method as long as the largest arms are significantly longer than the smallest ones.



Arm based sequencing

In sequencing we sort the moment arms and reduces power to thruster pairs; first for those with smallest arms and further on until power requirement is fulfilled. This method has the disadvantage that it makes some thrusters work at very high power, hence suffering from the relation $p_j \propto t_j^{\beta}$, and if pitch controlled units also the idle power.

Numeric example

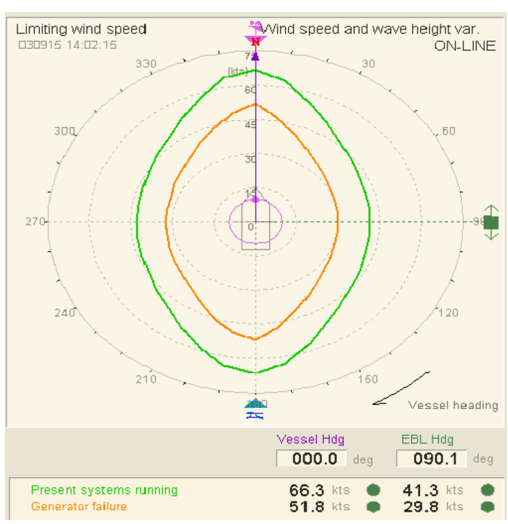
For the configuration example above with six tunnel thrusters each of 2,500kW, assume connected switchboards and a lateral thrust demand of 100 tonnes and a moment demand of 1,000 tonnes*m. This would require power consumption of approx. 9,500 kW. Imposing power limitation of 8,000 kW will result in the following obtained thrust with heading priority active:

Phase back procedure	**Lateral force (tonnes)**	**Moment (tonnes * m)**
Percentage phase back	84	835
Armed weighted phase back	83	935
Armed based sequencing	81	832

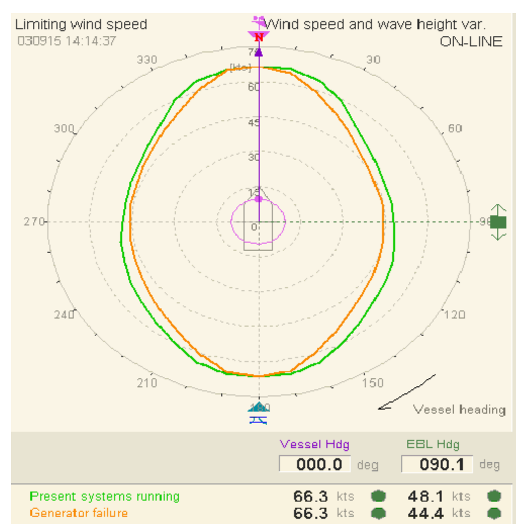
Power Optimisation

Even though armed weighted phase back seems favourable, the best way to handle the power limitation is to incorporate it into the optimisation process. The following figures show an example of a Capability plot for a vessel with two switchboards (splitted) with two generators each.

.



Normal percentage wise phase back



Power included in optimisation

Legend:

Green curve – Normal operation all generators running

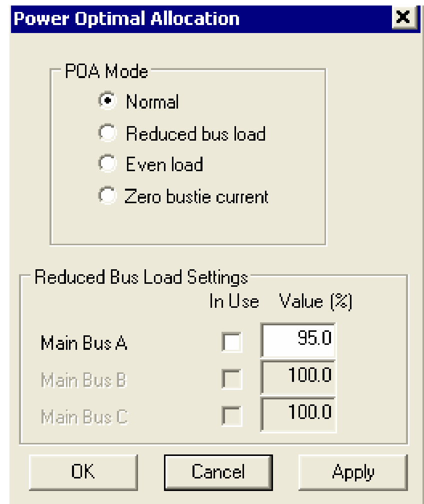
Orange curve – Loss of one generator on one switchboard

The positive effect of power optimisation is evident both in normal working condition and in the degraded case.

Special Features

The power optimisation may be also used to achieve special effects. The thruster allocation may e.g. be used in duality to the power management system, i.e. consumer control as a counterpart to load sharing. Looking at two split switchboards the optimisation may provide:

- Equal percentage load on each switchboard (Even Lode mode)
- Operator specified max load on one switchboard (Reduced Bus Load mode)
- Minimum bus tie current with connected switchboards(Zero Bus Tie Current mode)



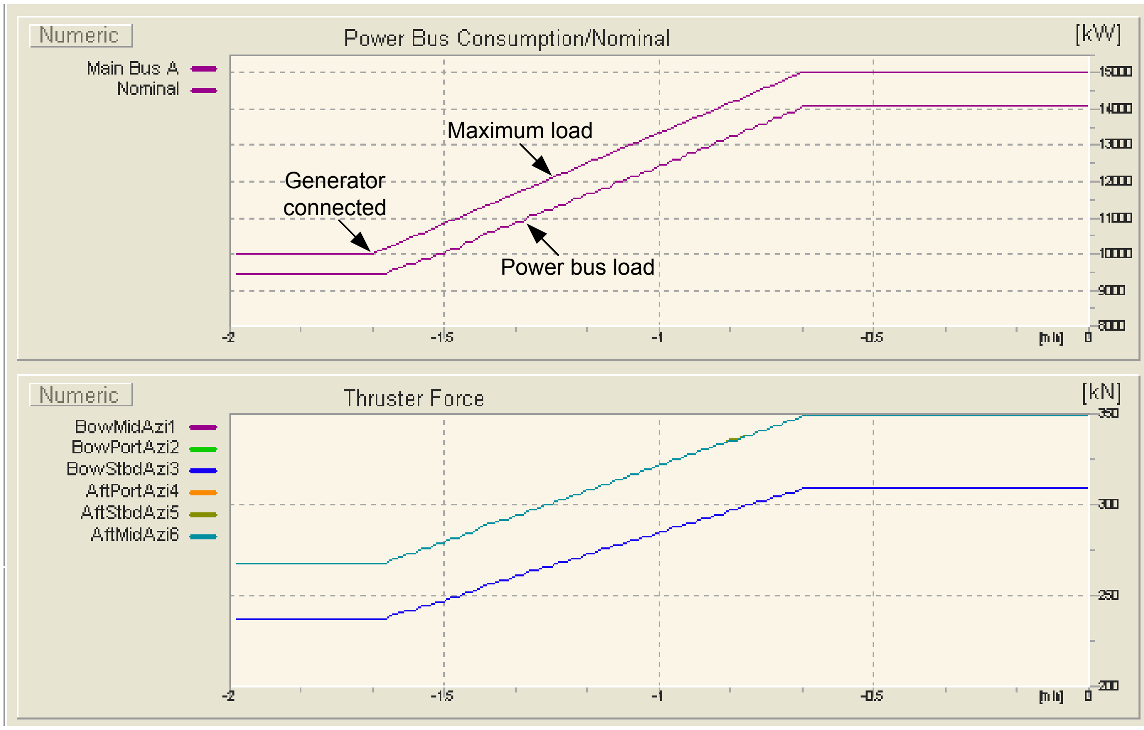
Even Load mode

The thrust is allocated so that the load is as even and as low as possible on all switchboards. The mode can also be used to prevent automatic standby start of generators and to give less wear and tear on the generators sets.

Reduced Bus Load mode

The operator can specify wanted maximum power consumption on one or more buses. The DP system will allocate thrust so the limits are normally not exceeded. The limits will be exceeded only to avoid insufficient thrust at high thrust demands and will hence not reduce the DP capability in any way. The mode can be used to prevent automatic standby start of generators. It can also be used to increase load on a bus to “clean” the diesel engines and to avoid overloading a recently started generator set.

The figure below illustrates the ramping up of generator load for a recently connected generator.

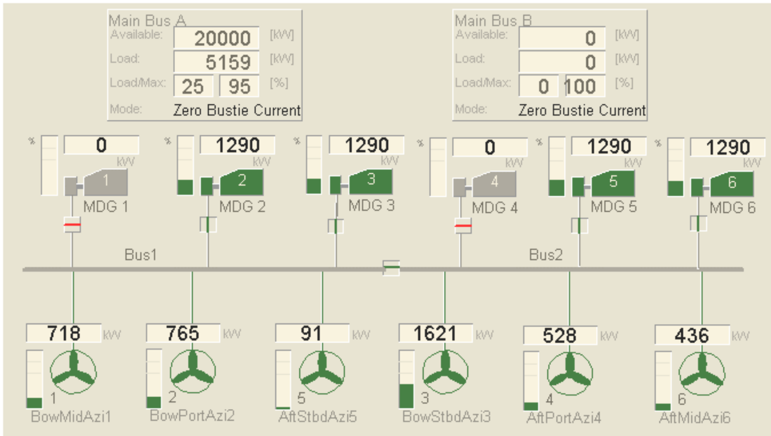


Zero Bus Tie Current mode

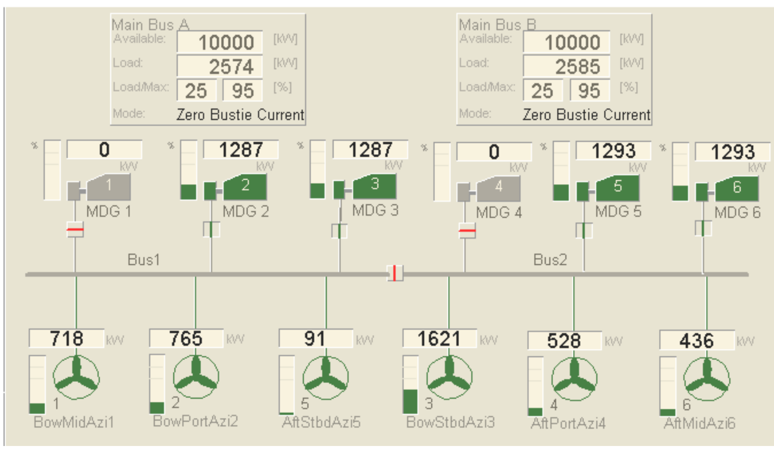
In this mode the thrust is allocated so that the current through the bus tie breakers are as low as possible, hence providing the safest possible mode for bus tie breaker operations (open/close breaker).

The following simulation illustrates how the consumer control works.

The first two figures show power plant configuration with closed an open bus tie running *Zero Bus Tie Current* mode.



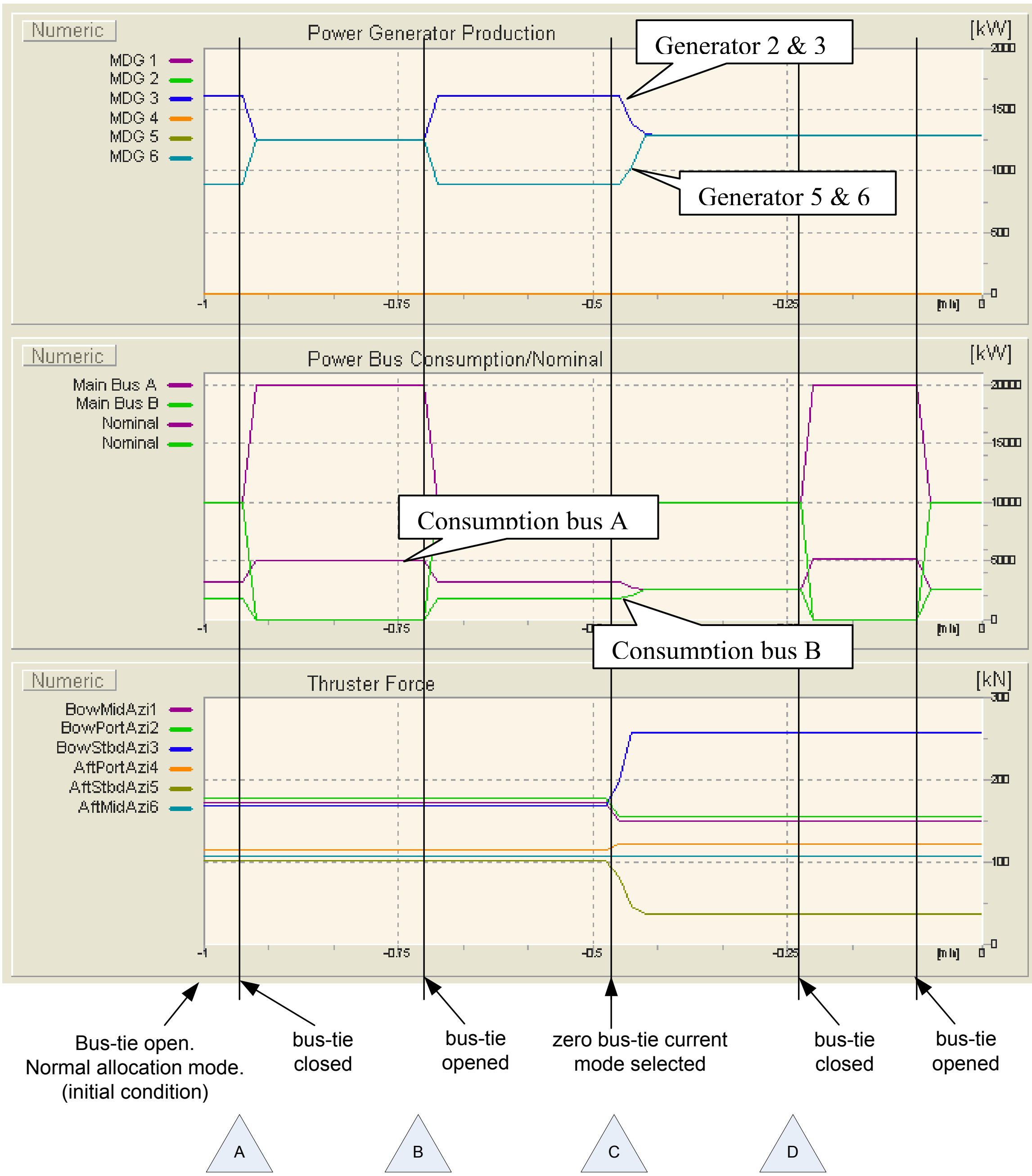
Closed bus tie



Open bus tie

As can be observed there is only marginal changes in the power distribution between the generators.

The trend curves below illustrate the effects in more detail. The scenario is indicated with arrows at the bottom of the graphs.



First we observe a redistribution of power among the generators when the bus tie is closed (A) and reopened (B). The bus tie operation has no effect on the thrusters (lowest part of graph). When the *Zero Bus Tie Current* is selected with still open bus tie (C), we observe a necessary redistribution of thrust and corresponding generator loads to minimize the bus tie current if the two halves should be connected. At closing the bus tie (D) there is no change in neither power distribution between generators as well as thrust distribution between the thrusters.