NONLINEAR CONTROL OF MARINE POWER GENERATION SYSTEMS

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ABSTRACT

A state space model of a marine power generation system consisting of two synchronous generators powered by diesel engines is presented. Special care has to be taken for such systems with the lack of a fixed network frequency and voltage. The model is developed and presented in a compact vector form suitable for control theory purpose. A nonlinear control law is derived compensating for the nonlinear generator dynamics. The control objective is stabilization of busbar voltage and frequency during large load changing. The nonlinear controller takes care of the generator speeds, and an additional PI-controller adds integral action for the voltage. Two simulations are performed comparing the nonlinear control law between exact plant modelling and reduced plant modelling by neglecting fast dynamics. The simulations showed good performance for a total load step change of 50%. The speed and voltage drop were less than 5%.

Keywords: Marine power generation, nonlinear control, modelling and simulation

1 INTRODUCTION

The electrical power demand for marine applications has increased heavily the last decades, mostly due to the increased use of electric propulsion systems for ships. Installed power typically range from 10 - 100 MW for different kind of ships, and the configuration of the electrical systems also varies with type of ship and manufacturer. One common factor for all the ships with electric propulsion is that the power production is split-up in several smaller units. This is due to safety and economical reasons. The main advantages with such systems compared to conventional systems are fuel saving, high reliability, high flexibility with engine room arrangement and simplified maintenance [1].

Special purpose vessels with dynamic positioning (DP) and thruster assisted mooring will often experience highly varying thruster loads which may lead to difficulties with power generation control. Synchronous generators are highly nonlinear when it comes to large load variations and with PID controllers for voltage and frequency some instability problems may occur and trip the circuit breakers.

Nonlinear control of power generation system has been a subject of interest for many years and the use of feedback linearization is well known [6]. Also nonlinear control of multimachine systems has been considered [5].

However most interest has been paid on Single-Machine Infinite Bus systems (SMIB) as in landbased installations. For marine power system a lack of external network complicates the frequency control (no synchronizing network frequency). Also for marine systems several generation units (typically 4-8 units) are working in parallel. All these interacts with each other, which may yield power oscillations between them. Hence a supervisory multivariable controller would be appreciable. The contribution in this paper is presenting a compact state space model of a power generation system with no infinite busbar as in marine power systems. This model is written in a compact vector form for control purpose. Then a nonlinear control law is suggested and tested by a simulated example.

Outline of the paper: In Section 2 the state space model of two generators supplying a common load is presented. In Section 3 a nonlinear control law is derived. Simulation results are shown in Section 4 and finally some concluding remarks are drawn in Section 5.

2 PLANT MODEL

The system to be modelled consists of two synchronous generators powered by diesel engines and supplying a common load. An aggregate load model is used, specifying total active (P_{tot}) and reactive (Q_{tot}) power and hence compute an equivalent impedance. For simplicity only constant impedance model is used in this paper, but other load models such as constant power may also be included.

Other work on nonlinear power control mainly concentrates on landbased installations with controlling a single machine connected to an infinite bus system. The well known generator models are then used with a fixed network-frequency and voltage as input. When modelling a marine power system there is no fixed network frequency and voltage, these are dependent on the load and the other generators. In this paper well known models for each component are used, and following the derivation in [4] a compact state space model in vector form is proposed. This is done to make use of more advanced control theory, which often assumes mathematical models in a certain frame. The disadvantage with writing the models in such abstract terms is that the basic electrical terms disappear in the equations.

There are usually more than two generators in a marine power system and the modelling below is not fixed to a specific number. One generator is used as a reference when it comes relative power angles. The power angle of this reference generator is computed by the load equations. At the end an overall state space model is presented in vector form with two generators as an example.

2.1 Synchronous generators

A 3^{rd} order nonlinear state-space model based upon [2] is used for each of the synchronous generators. All the variables and parameters are defined below.

Definitions:

States:

$\Delta\delta_i$	:	Relative power angle referred to gen. no.1[rad].
Ω_i	:	Shaft speed [pu].
u'_{qi}	:	Voltage proportional to field current [pu].

Inputs:

u_{di}	:	d-axis terminal voltage [pu].
u_{qi}	:	q-axis terminal voltage [pu].
Ω_1	:	Shaft speed gen. no. 1 [pu].
Ω_j	:	Shaft speed of the other generators [pu].
T_{mi}	:	Mechanical shaft torque [pu].
u_{fi}	:	Field voltage [pu].

Outputs:

i_{di}	:	d-axis stator current [pu].
i_{qi}	:	q-axis stator current.[pu].
Ω_{ai}	:	Shaft speed [pu].
P_i	:	Active power [pu].
Q_i	:	Reactive power [pu].

Parameters:

ω_N	:	Nominal electrical angular frequency [rad/s].
T_{ai}	:	Mechanical time constant [s]. T_a equals $\Omega_{ref}\frac{J}{T_{ref}}$, where J is the total inertia.
f_{ri}	:	Friction coefficient [pu].
D_i	:	Damping coefficient [pu].
T'_{doi}	:	Field winding time constant [s].
x_{di}	:	d-axis reactance [pu].
x'_{di}	:	d-axis transient reactance [pu].
x_{qi}	:	q-axis reactance [pu].
x_{afi}	:	Mutual reactance between field winding and armature winding [pu].
r_{fi}	:	Field winding resistance [pu].

State equations in per unit:

$$\Delta\dot{\delta}_i = \omega_N(\Omega_i - \Omega_1) \tag{1a}$$

$$\dot{\Omega}_i = \frac{1}{T_{ai}}[T_{mi} - T_{ei} - \sum_{j\neq i} D_{ij}(\Omega_i - \Omega_j) - f_i\Omega_i] \tag{1b}$$

$$\dot{u}'_{qi} = \frac{1}{T'_{doi}}[-u'_{qi} - (x_{di} - x'_{di})i_{di} + u_{dfi}] \tag{1c}$$

Algebraic equations:

$$u_{dfi} = \frac{x_{afi}}{r_{fi}}u_{fi}, \quad i_{di} = \frac{u'_{qi} - \frac{u_{qi}}{\Omega_i}}{x'_{di}}, \quad i_{qi} = \frac{u_{di}}{\Omega_i x_{qi}} \tag{2}$$

$$T_{ei} = i_{qi}[x_{afi}i_{fi} - i_{di}(x_{di} - x_{qi})] \tag{3}$$

$$x_{afi}i_{fi} = u'_{qi} + (x_{di} - x'_{di})i_{di} \tag{4}$$

2.2 Diesel engines

The medium speed diesel engine is modelled as a 1^{st} order model [3].

$$\dot{T}_m = \frac{1}{T_{DE}}(-T_m + z) \tag{5}$$

where T_m is mechanical shaft torque [pu], T_{DE} is diesel dynamic time constant [s] and z is fuel-pump index [pu].

2.3 Load modelling

The modelling of loads and modelling of the interconnection of the different generators are done by algebraic equations and with reference to the phasor diagram in Figure 1. The basic idea is to add vectorial the current outputs from the generator models and compute the busbar voltage from the specified load characteristic, e.g. a constant impedance in this case. The load equations are given below:

$$(r + jx) = \left(\frac{1}{P_{tot} + jQ_{tot}}\right)^* \tag{6}$$

* denotes complex conjugate.

$$I_i = \sqrt{i_{di}^2 + i_{qi}^2}\, e^{-j(\psi_i - \delta_i)} \tag{7}$$

where $\psi_i = \arctan(i_{di}/i_{qi})$.

$$i_{d1i} = I_i \sin(\phi_i + \delta_1) \tag{8}$$

$$i_{q1i} = I_i \cos(\phi_i + \delta_1) \tag{9}$$

$$i_{d1tot} = \sum_{i=1}^{p} i_{d1i}, \quad i_{q1tot} = \sum_{i=1}^{p} i_{q1i} \tag{10}$$

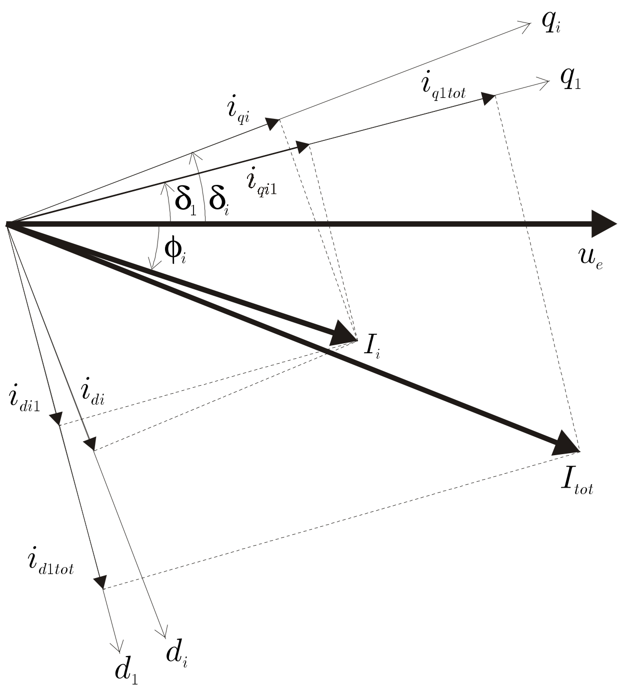

Figure 1: Phasor diagram showing transformation of current unit i to the d-q frame of unit 1.

$$u_{d1} = ri_{d1tot} - xi_{q1tot} \quad (11a)$$
$$u_{q1} = ri_{q1tot} + xi_{d1tot} \quad (11b)$$
$$u_e = \sqrt{u_{d1}^2 + u_{q1}^2} \quad (11c)$$
$$\delta_1 = \tan^{-1}(u_{d1}/u_{q2}), \quad \delta_i = \Delta\delta_i + \delta_1 \quad (11d)$$
$$u_{di} = u_e \sin(\delta_i), \quad u_{qi} = u_e \cos(\delta_i) \quad (11e)$$

2.4 Vector form

In this section a compact state space model of the whole system with two synchronous generators is presented.

Define: $\mathbf{x} = [\Omega_1, u'_{q1}, \Delta\delta_2, \Omega_2, u'_{q2}, T_{m1}, T_{m2}]^T$, $\mathbf{u_g} = [u_{d1}, u_{q1}, u_{d2}, u_{q2}]^T$, $\mathbf{u} = [z_1, u_{f1}, z_2, u_{f2}]^T$ and $\mathbf{w} = [r_L, x_L]^T$

Synchronous generators:

$$\dot{x}_1 = -a_1 u_{g1}\frac{x_2}{x_1} + a_2 u_{g1} u_{g2}\frac{1}{x_1^2} \quad (12a)$$
$$-a_{11}x_1 + a_{14}x_4 + a_{16}x_6 \quad (12b)$$
$$\dot{x}_2 = a_3 u_{g2}\frac{1}{x_1} - a_{22}x_2 + b_{22}u_2 \quad (12c)$$
$$\dot{x}_3 = -a_{31}x_1 + a_{34}x_4 \quad (12d)$$
$$\dot{x}_4 = -a_1 u_{g3}\frac{x_5}{x_4} + a_2 u_{g3} u_{g4}\frac{1}{x_4^2} \quad (12e)$$
$$+a_{41}x_1 - a_{44}x_4 + a_{47}x_7 \quad (12f)$$
$$\dot{x}_5 = a_3 u_{g4}\frac{1}{x_4} - a_{55}x_5 + b_{54}u_4 \quad (12g)$$

Diesel engines:

$$\dot{x}_6 = -a_{66}x_6 + b_{61}u_1 \quad (13a)$$
$$\dot{x}_7 = -a_{77}x_7 + b_{73}u_3 \quad (13b)$$

where:

$a_1 = \frac{1}{x'_d T_a}$, $a_{22} = a_{55} = \frac{x_d}{x'_d T'_{do}}$

$a_2 = \frac{x_q - x'_d}{T_a x_q x'_d}$, $a_{31} = a_{34} = \omega_N$

$a_3 = \frac{(x_d - x'_d)}{x'_d T'_{do}}$, $a_{66} = a_{77} = b_{61} =$

$a_{11} = a_{44} = \frac{D+f_r}{T_a}$, $b_{73} = \frac{1}{T_{DE}}$

$a_{14} = a_{41} = \frac{D}{T_a}$, $b_{22} = b_{54} = \frac{x_{af}}{r_f T'_{do}}$

$a_{16} = a_{47} = \frac{1}{T_a}$

are positive parameters.

Load module (algebraic equations):

$$u_{g1} = w_1 i_{d1tot} - w_2 i_{q1tot} \quad (14a)$$
$$u_{g2} = w_2 i_{q1tot} + w_2 i_{d1tot} \quad (14b)$$
$$u_{g3} = \sqrt{u_{g1}^2 + u_{g2}^2}\sin[x_3 + \tan^{-1}(\frac{u_{g1}}{u_{g2}})] \quad (14c)$$
$$u_{g4} = \sqrt{u_{g1}^2 + u_{g2}^2}\cos[x_3 + \tan^{-1}(\frac{u_{g1}}{u_{g2}})] \quad (14d)$$

where:

$$i_{d1tot} = i_{d1} + \sqrt{i_{d2}^2 + i_{q2}^2}\sin[\tan^{-1}(\frac{i_{d2}}{i_{q2}}) + \tan^{-1}(\frac{u_{g1}}{u_{g2}})] \quad (15)$$
$$i_{q1tot} = i_{q1} + \sqrt{i_{d2}^2 + i_{q2}^2}\cos[\tan^{-1}(\frac{i_{d2}}{i_{q2}}) + \tan^{-1}(\frac{u_{g1}}{u_{g2}})] \quad (16)$$

where:

$$i_{d1} = c_1 x_2 - c_1\frac{u_{g2}}{x_1} \quad (17)$$
$$i_{q1} = c_2\frac{u_{g1}}{x_1} \quad (18)$$
$$i_{d2} = c_1 x_5 - c_1\frac{u_{g4}}{x_4} \quad (19)$$
$$i_{q2} = c_2\frac{u_{g3}}{x_4} \quad (20)$$

where $c_1 = 1/x'_d$ and $c_2 = 1/x_q$.

Nonlinear state-space model

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{f}(\mathbf{x}, \mathbf{u_g}) + \mathbf{B}\mathbf{u} \quad (21)$$
$$\mathbf{u_g} = \Phi(\mathbf{x}, \mathbf{w}, \mathbf{u_g}) \quad (22)$$

where Φ is an implicit equation given in component

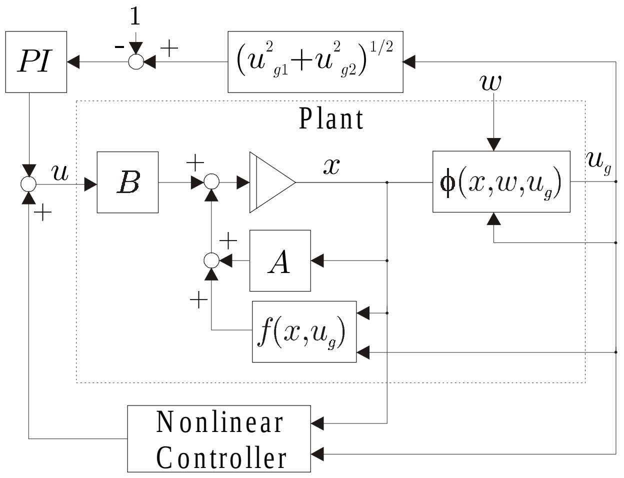

Figure 2: Block diagram showing model structure and control strategy.

form by (14), and

$$\mathbf{A} = \begin{bmatrix} -a_{11} & 0 & 0 & a_{14} & 0 & a_{16} & 0 \\ 0 & -a_{22} & 0 & 0 & 0 & 0 & 0 \\ -a_{31} & 0 & 0 & a_{34} & 0 & 0 & 0 \\ a_{41} & 0 & 0 & -a_{44} & 0 & 0 & a_{47} \\ 0 & 0 & 0 & 0 & -a_{55} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -a_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -a_{77} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & b_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{54} \\ b_{61} & 0 & 0 & 0 \\ 0 & 0 & b_{73} & 0 \end{bmatrix}$$

and

$$\mathbf{f}(\mathbf{x}, \mathbf{u_g}) = \begin{bmatrix} -a_1 \frac{x_2}{x_1} u_{g1} + a_2 \frac{1}{x_1^2} u_{g1} u_{g2} \\ a_3 \frac{1}{x_1} u_{g2} \\ 0 \\ -a_1 \frac{x_5}{x_4} u_{g3} + a_2 \frac{1}{x_4^2} u_{g3} u_{g4} \\ a_3 \frac{1}{x_4} u_{g4} \\ 0 \\ 0 \end{bmatrix}$$

The control objective is regulation of:

$$\mathbf{y} = [x_1, x_4, \|\mathbf{C}\mathbf{u_g}\|_2]^T,$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{23}$$

3 NONLINEAR CONTROL

Figure 2 shows the model structure and how the nonlinear controller is implemented. There are basically two non-linear terms, $\mathbf{f}(\mathbf{x}, \mathbf{u_g})$ which reflects the generator dynamics, and $\mathbf{u_g} = \Phi(\mathbf{x}, \mathbf{w}, \mathbf{u_g})$ which reflects the interconnection of the generators and the load modelling. The second nonlinearity is highly sensitive to modelling errors mostly due to the chosen load model strategy.

In this paper a control strategy only compensating for the non-linear term $\mathbf{f}(\mathbf{x}, \mathbf{u_g})$ is considered. The linear part of the system can be stabilized by using linear theory if the nonlinear part is cancelled out by the controller.

Since the model contains dynamics between fuel index and shaft torque (diesel engine), the B matrix has only zeros in row 1 and 4. That is, there are no inputs which can directly cancel out the nonlinear terms f_1 and f_4. This can be solved by using the shaft torque to cancel out the nonlinearity. The following derivation is equal for both generators.

$$x_1 = \sum_{j=1}^{5} a_{1j} x_j + f_1(\mathbf{x}, \mathbf{u_g}) + a_{16} x_6 \tag{24}$$

choosing:

$$a_{16} x_6 = -f_1(\mathbf{x}, \mathbf{u_g}) \tag{25}$$

compensates the nonlinear term. Thus

$$\dot{x}_6 = -\frac{1}{a_{16}} \dot{f}_1 = -a_{66} x_6 + b_{61} u_1 \tag{26}$$

This yields:

$$u_1 = \frac{1}{b_{61}} (a_{66} x_6 - \frac{1}{a_{16}} \dot{f}_1) \tag{27}$$

Equation (27) is perfectly solvable but the expression gets quite complicated. However, the diesel engine time constant (<1s.) is much faster than the synchronous generators time constants (typically 1-10s.). For simplicity the diesel engine dynamic is neglected when computing the nonlinear control law. This should have no major impact on the results, and the derivation of the controller is highly simplified. In the simulations, however, the diesel dynamics is included in the plant model itself showing the effect of neglecting this in the control law.

3.1 Reduced order model

The system is reduced to a fifth-order system by removing the diesel dynamic states, that is $\dot{x}_6 = \dot{x}_7 = 0$, such that:

$$x_6 = \frac{b_{61}}{a_{66}} u_1 = u_1 \tag{28}$$

$$x_7 = \frac{b_{73}}{a_{77}} u_3 = u_3 \tag{29}$$

The new B matrix is then given by

$$\mathbf{B}_r = \begin{bmatrix} a_{16} & 0 & 0 & 0 \\ 0 & b_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & a_{47} & 0 \\ 0 & 0 & 0 & b_{54} \end{bmatrix} \tag{30}$$

The subscript r denotes the reduced order model such that $\mathbf{x}_r = [x_1, x_2, x_3, x_4, x_5]^T$. The matrix $\mathbf{A}_r$

is computed by removing the last two rows and last two coloums from $\mathbf{A}$ and $\mathbf{f}_r = [f_1, f_2, f_3, f_4, f_5]^T$.

The model is then transformed such that the origin is the desired working point. This is done by selecting the new states as $\tilde{\mathbf{x}}_r = \mathbf{x}_r - \mathbf{x_0}$, where $\mathbf{x_0}$ is the current working point. This yields:

$$\dot{\tilde{\mathbf{x}}}_r = \mathbf{A}_r(\tilde{\mathbf{x}}_r + \mathbf{x_0}) + \mathbf{f}_r(\tilde{\mathbf{x}}_r + \mathbf{x_0}, \mathbf{u_g}) + \mathbf{B}_r\mathbf{u} \qquad (31)$$

3.2 Nonlinear control law

The control law $\mathbf{u}$ is selected as:

$$\begin{aligned} \mathbf{u} &= \mathbf{B}_r^{\dagger}[-\mathbf{f}_r(\tilde{\mathbf{x}}_r + \mathbf{x_0}, \mathbf{u_g}) \\ &\quad -\mathbf{K}\tilde{\mathbf{x}}_r - \mathbf{K_I}\mathbf{v} - \mathbf{A}_r\mathbf{x_0}] \qquad (32a) \\ \dot{\mathbf{v}} &= \tilde{\mathbf{x}}_r \qquad (32b) \end{aligned}$$

where $\mathbf{B}_r^{\dagger} = \mathbf{B}_r^T(\mathbf{B}_r\mathbf{B}_r^T)^{-1}$ is the pseudoinverse of $\mathbf{B}_r$, and $\mathbf{K}$ is a proportional gain matrix and $\mathbf{K_I}$ is an integral gain matrix. The system is then reduced to the linear error dynamics.

$$\begin{aligned} \dot{\tilde{\mathbf{x}}}_r &= (\mathbf{A}_r - \mathbf{K})\tilde{\mathbf{x}}_r - \mathbf{K_I}\mathbf{v} \qquad (33a) \\ \dot{\mathbf{v}} &= \tilde{\mathbf{x}}_r \qquad (33b) \end{aligned}$$

where $\mathbf{K}$ and $\mathbf{K_I}$ can be chosen by pole placement.

Hence $\tilde{\mathbf{x}}_r$ converges to zero. Finally the bus bar voltage $\sqrt{u_{g1}^2 + u_{g2}^2}$ is controlled by using a PI-control law, see outer loop in Figure 2.

Only two of the states are directly measured, which necessitates the need for a state observer. The states are assumed available in this paper, but for future work the impact of introducing an observer will be investigated.

4 SIMULATION STUDIES

Simulations were performed with the control law (32). The matrices $\mathbf{K}$ and $\mathbf{K_I}$ were chosen as:

$$\mathbf{K} = \begin{bmatrix} 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{K_I} = \begin{bmatrix} 0.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0 & 0 \\ 0 & 0 & 0 & 0.3 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The control law (32) stabilizes the states $\tilde{\mathbf{x}}_r$ to zero. However when a disturbance enter the plant in form of a total load change in either active or reactive power or both, only the speed of the generators and the voltage should remain constant, the other states would necessary have to change. By choosing the matrices as above only the generator speeds and the relative power angle are forced to be controlled, the other states will naturally follow due to the power balance and the system physics.

As simulation case a step in total active power load (P_{tot}) at time 10s from 1pu to 1.5pu, and a step in total reactive power (Q_{tot}) at time 40s from 1pu to 1.5pu.

Two simulations were performed, one with reduced model as the plant and one with the full model as the plant. The load is shared equally between the two generators. Figures 3 and 4 show the results.

5 CONCLUDING REMARKS

A nonlinear state space model was derived for a marine power generation system with two diesel generators supplying a common load. This model was written in a compact vector form and a nonlinear control law was found for stabilization and disturbance rejection. To investigate the behavior of the nonlinear control law a simulation case with large steps (50%) in the disturbance signals, total active load and total reactive load. Two simulations were performed comparing the performance for an exact model with a model with neglected fast dynamics. As expected the performance was excellent with an exact plant model. Even with neglecting some dynamics the performance was satisfactory with only a frequency drop at about 2% and voltage drop at about 5%, which is quite good considering the large load steps. This means that the controller shows a certain set of robustness.

REFERENCES

[1] *1st International Conference on Diesel Electric Propulsion - a Cost Effective Solution.* Norwegian Society of Chartered Engineer, 1996.

[2] J. Arrillaga and C. P. Arnold. *Computer Analysis of Power Systems.* John Wiley and Sons Ltd., 1990.

[3] T. I. Fossen. *Guidance and Control of Ocean Vehicles.* John Wiley & Sons, 1994.

[4] J. F. Hansen, A. K. Ådnanes, and T. I. Fossen. Modelling, simulation and multivariable model-based predictive control of marine power generation system. Proc. of the IFAC Conf. on Control Appl. in Marine Systems, CAMS 98, Fukuoka, Japan. Oct., 1998.

[5] Q. Lu and Y. Sun. Nonlinear stabilizing control of multimachine systems. *IEEE Transactions on Power Systems*, 4(1):236–241, 1989.

[6] W. M. A. Zajaczkowski. Multivariable non-linear controller for a synchronous generator. *Optimal Control Applications and Methods*, 15:49–65, 1994.

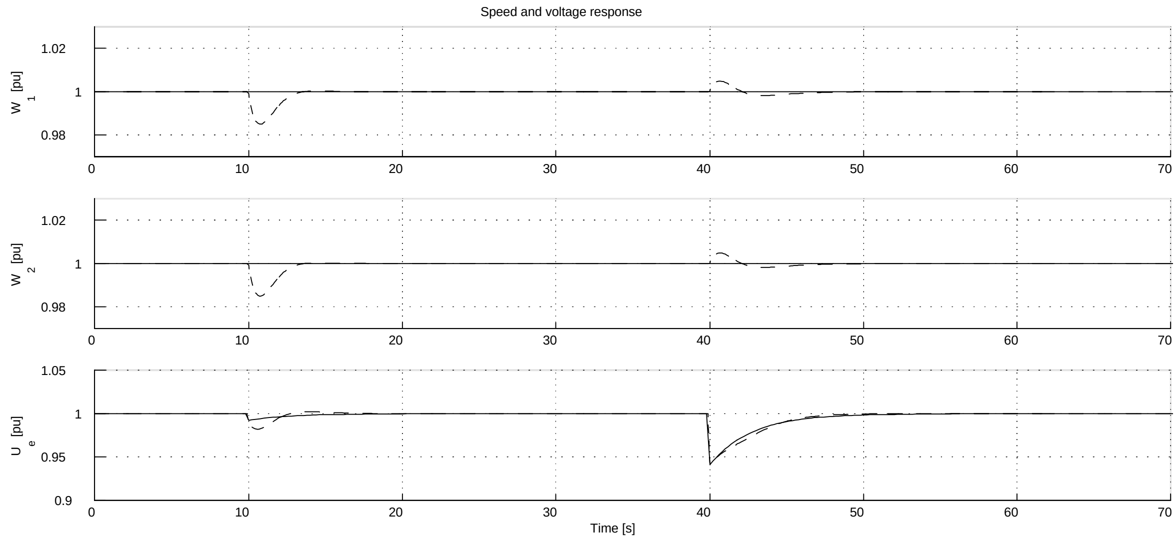

Figure 3: Speed (w_1, w_2) and voltage (U_e) versus time response for a step in power load with the nonlinear control law. (-) reduced order plant model, (- -) full plant model.

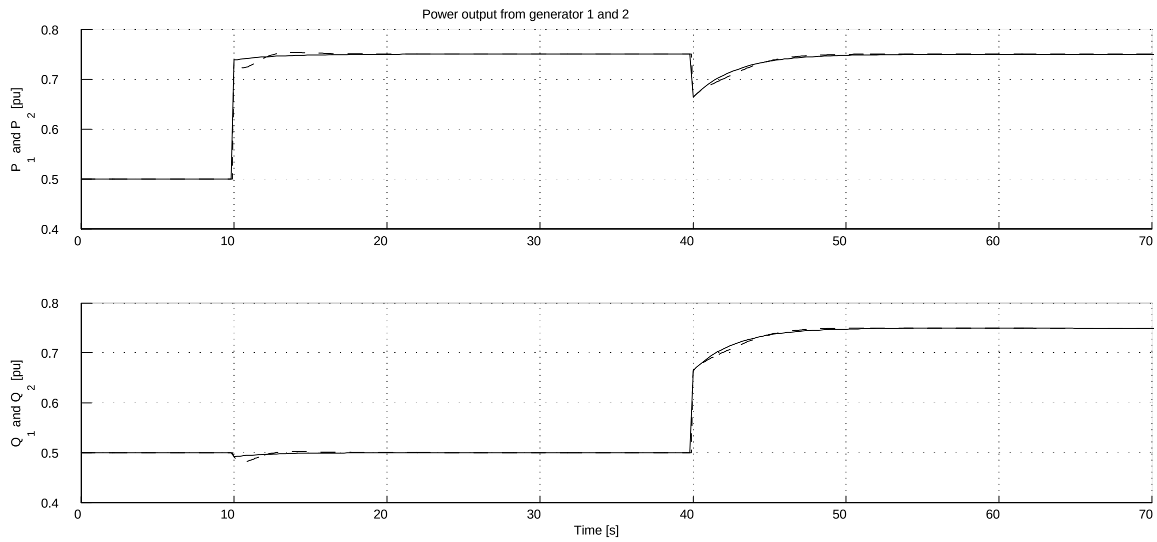

Figure 4: Active power (P_i) and reactive power (Q_i) versus time, from the generators. (-) reduced order plant model, (- -) full plant model.