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Development of a Multi-Variable Control for a Parallel Connection of the Flywheel Generators EZ3 and EZ4

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ABSTRACT

The power supply of ASDEX Upgrade comprises the flywheel generators EZ3 (500 MJ / 144 MVA) and EZ4 (650 MJ / 220 MVA). Each generator feeds its own 10.5 kV system. For quasi-stationary advanced tokamak experiments with extended flattop phase, the flywheel generators EZ3 and EZ4 must be connected in parallel so that the available power and energy can be fully exploited. The dynamic load requirements of ASDEX Upgrade and the different electrical and mechanical parameters of the two synchronous machines require a multi-variable control in order to achieve a defined load distribution on both generators. This report describes the design and performance of a multi-variable control which fulfils all requirements for a reliable and safe operation of the parallel connected flywheel generators.

Table of contents

Abstract 2
Table of contents 3

1. BACKGROUND AND OBJECTIVE 4

2. INTRODUCTION 7

3. CONTROLLER DESIGN 9

3.1 Control Model for Two Paralleled Flywheel Generators 10

3.2 Design of the Feedback Controller 12

4. DERIVATION OF A LOAD MODEL 16

5. BEHAVIOUR ANALYSIS AND RESULTS OF THE PARALLELED GENERATOR SYSTEM WITH MULTI-VARIABLE CONTROL 19

5.1 Dynamic Behavior under Extreme Load Conditions 19

5.2 Response on Sudden Load Step 20

5.3 Parametrical study : Variation of Generator Parameters 22
5.3.1 Changing parameters of the generators 22
5.3.2 Worst case parameters of paralleled generators 23

5.4 Circular Current 26

5.5 Operational Region of the Power Factor in the Paralleled Generator System 27

6. CONCLUSION 30

7. REFERENCES 31

APPENDIX 32

Appendix 1. VC++ Source Program of Load model in C-interface of Simplorer 32

Appendix 2. Overview on the summary of simulation results 41

1 Background and Objective

The power supply of ASDEX Upgrade comprises the flywheel generators EZ3 (500 MJ / 144 MVA) and EZ4 (650 MJ / 220 MVA). The time of construction of the flywheel generators EZ3 and EZ4 are ten years apart from each other and the electrical and mechanical properties of the machines are quite different (see Table 1). Therefore, each generator feeds its own 10.5 kV system.

Table 1. External parameters of the flywheel generators EZ3 and EZ4

Flywheel generator	**EZ3**	**EZ4**
Design voltage	$U_n = 10.5$ kV	$U_n = 10.5$ kV
Nominal apparent power in pulsed operation	$S_n = 144$ MVA $\cos\varphi = 0.93$	$S_n = 220$ MVA $\cos\varphi = 0.49$
Nominal frequency	$f_n = 100$ Hz	$f_n = 100$ Hz
Moment of inertia	$J = 90400$ kgm^2	$J = 120300$ kgm^2
Initial rotational speed	$n=1650$min^{-1}	$n=1650$min^{-1}
Synchronous reactance, direct axis (unsaturated/saturated)	$x_d=4.5$/ $x_{ds}= 3.6$	$x_d= 3.14$ / $x_{ds}= 2.57$
Unsaturated synchronous reactance, quadrature axis	$x_q = 3.1$	$x_q = 1.62$
Subtransient reactance, direct axis	$x_d'' = 0.186$	$x_d'' = 0.175$
Subtransient reactance, quadrature axis	$x_q'' = 0.19$	$x_q'' = 0.21$
Transient reactance, direct axis	$x_{du}' = 0.68$	$x_d' = 0.328$
Transient short-circuit time constant	$T_d' = 0.55$ s	$T_d' = 0.204$ s
Subtransient short-circuit time constant	$T_d'' = 0.03$ s	$T_d'' = 0.021$ s
Winding resistance at T=20°C	$R_1 = 5.9$ mΩ	$R_1 = 2.68$ mΩ

For advanced tokamak experiments with elongated plasma flattop-phase a parallel operation of both flywheel generators would be advantageous for the following reasons:

- A synchronous discharge of both flywheels would be guaranteed, i.e. the available flywheel energy can be <u>fully</u> exploited without overloading one of the generators (optimum load sharing). Without parallel connection the load pulse must be terminated as soon as one of the flywheels is unloaded even if there are, i.e, more than 200 MJ left in the other flywheel.

- A defined load distribution in the static and dynamic case will avoid that the power limits of the single machines (EZ3: 144 MVA, EZ4: 220 MVA) can be reached before the sum of available power (about 350 MVA) is exceeded. This point is of special importance for long pulse operation where, e.g., the deliverable apparent power from EZ3 will drop from 144 MVA at the beginning of the pulse to less than 100 MVA at the end of the pulse.
- The parallel connection of EZ3 and EZ4 will facilitate the technical feasibility of plasma experiments with different power demands (less boundary conditions from experimental power supply)
- The power quality will improve because the parallel connection brings a reduction of the subtransient generator reactance which leads to less distortion of the system voltage (improvement of performance of phase-commutated converters). With increasing power demand (commissioning of additional converter group with 135 MVA in 2001) this may become an important factor
- The reactive power compensation (RPC) modules which are or will be installed at generator EZ3 (altogether 120 MVAr) would be available for both generators as soon as the two machines are switched in parallel
- On a long-term basis the parallel connection of EZ3 and EZ4 provides a better base for an extension of the existing power supply (by RPC modules, energy storage modules or an additional flywheel generator)
- Last but not least: The parallel connection of EZ3 and EZ4 can be realised in such a way that both generators can be operated in single operation mode (like in the past) if problems with the parallel operation arise (e.g. due to malfunctions of the controller or paralleling link)

In the 10.5 kV systems of EZ3 and EZ4 sudden load changes can occur and the power frequencies may decrease from 110 Hz to 85 Hz. These requirements and the different eletrical and mechanical parameters of both generators require detailed numerical models for an investigation of the stability limits of a parallel operation of the two machines on one common busbar. The object of former studies was the derivation of detailed flywheel generator models from analytical

calculations and measurements [1], investigating the transient behaviour of the two parallel connected generators with a conventional controller [2] and the performance of paralleled generators with an optimised conventional controller (PI voltage controller with secondary PD controller circuit) [3]. Although the results achieved with this controller looked very promising, the applicability of such a controller is uncertain because this type of controller is sensitive to external disturbances (variation of machine parameters, harmonics, EMC problems).

This report describes the design and performance of a multi-variable controller which fulfils all requirements for a reliable and safe operation of parallel connected flywheel generators.

2 Introduction

In the existing power supply, the flywheel generators EZ3 and EZ4 are electrically isolated from each other and supply different loads, as shown in Fig. 1. As long as the busbar voltage of each generator is controlled and kept to a constant value, the generators can operate .

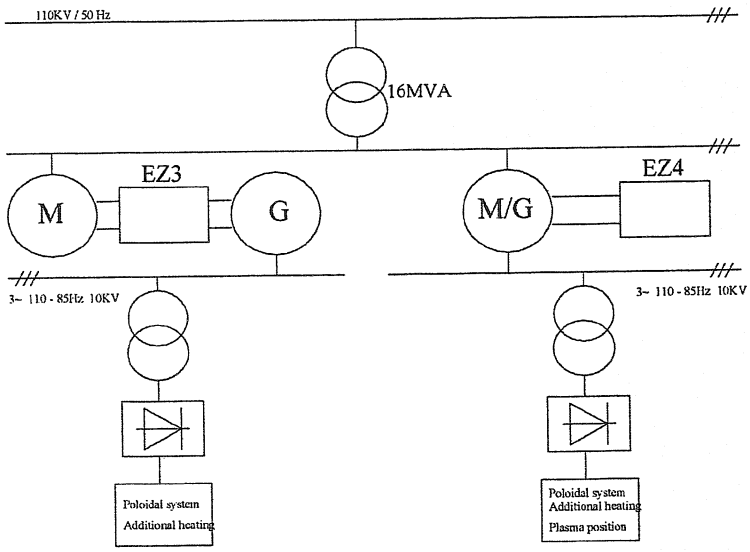


Figure 1: The existing work mode of generators EZ3 and EZ4

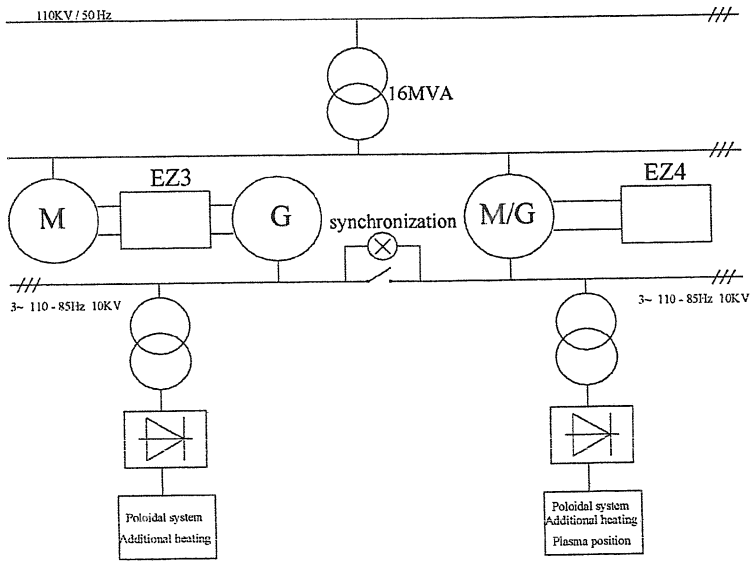


Figure 2: Future work mode of generators EZ3 and EZ4

After paralleling the two generators, they will form a power system as shown in Fig.2 . Besides the busbar voltage, the output power of each generator must also be controlled. Operation of two flywheel generators in parallel is quite different from operating synchronous generators in large networks. Features are :

- Limited flywheel energy and changing frequency
- Pulse operation of short time
- Fast and high load changes (e.g. power oscillations with 100MW in 100ms were measured at flywheel generator EZ3)

To operate safely, a detailed analysis must be performed and satisfactory solution for the following critical items must be provided:

- output voltage control of the two generators
- power-distribution between generator EZ3 and EZ4
- fast response during changing load
- static and dynamic stability of the operational region of the generator system
- fault analysis
- system protection
- parallel switch and work mode of the system
- engineering design and realization

3 Controller Design

In a parallel generator system the load power is supplied by two generators at the same time , the bus voltage must be kept constant, the power output of the two generators must be symmetrical according to their apparent power. So the variables to be controlled are power-distribution and bus voltage :

$$k = \frac{S_3}{S_4} = \frac{S_{n3}}{S_{n4}} \qquad (1)$$

u=10.5kV

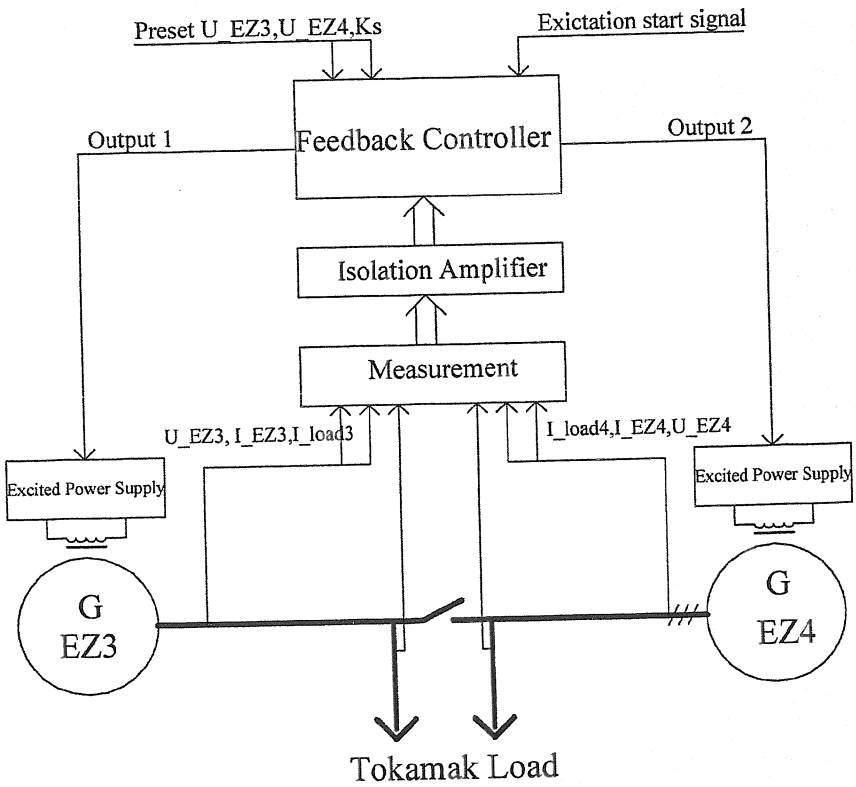


Figure 3: Power distribution and voltage controller for parallel connection of EZ3 and EZ4

At flywheel generators the bus voltage and power output are controlled by their excited power supplies, as show in Fig.3. The presetting values are compared to the real parameters of AC voltage and current of each generator by measurement. According to the algorithm in the feedback controller the necessary output of the

excited power supply can be calculated, and the corresponding signal to the a-controller of excited power supplies can be given. By change of excited voltage the object of desirable generator output can be reached.

3.1 Control Model for Two Parallel Flywheel Generators

The electromagnetic equation of the generators, which will be used next, can be written as follows :

$$
\begin{aligned}
&u_d = p\Psi_d - \Psi_q - ri_d - \Psi_q p\delta \;; && u_q = p\Psi_q + \Psi_d - ri_q + \Psi_d p\delta \\
&E_q^{'} = u_q + i_d x_d^{'} + i_q r \;; && E_d^{'} = u_d + i_q x_q^{'} + i_d r \\
&E_q^{''} = u_q + i_d x_d^{''} + i_q r \;; && E_d^{''} = u_d + i_q x_q^{''} + i_q r \\
&\Psi_d = -x_d(p) i_d + G(p) u_{fd} \;; && \Psi_q = -x_q(p) i_q
\end{aligned}
\tag{2}
$$

- p: $F(p) = p\int_0^{\infty} f(t) e^{-pt} dt$;
- computing reactance of direct axis:

$$x_d(p) = x_d - \frac{(x_{fd} x_{ad}^{\;2} + x_{kd} x_{ad}^{\;2} - 2x_{ad}^{\;3})p^2 + (x_{ad}^{\;2} R_{fd} + x_{ad}^{\;2} R_{kd})p}{(x_{fd} x_{kd} - x_{ad}^{\;2})p^2 + (x_{fd} R_{kd} + x_{kd} R_{fd})p + R_{fd} R_{kd}} \;;$$

- transfer function of direct axis:

$$G(p) = \frac{R_{kd} x_{ad} + (x_{ad}\, x_{kd} - x_{ad}^{\;2})p}{(x_{fd} x_{kd} - x_{ad}^{\;2})p^2 + (x_{fd} R_{kd} + x_{kd} R_{fd})p + R_{fd} R_{kd}} \;;$$

- computing reactance of quadrature axis:

$$x_q(p) = x_q - \frac{x_{aq}^{\;2} p}{x_{kq} p + R_{kq}}$$

- δ: rotor angle of generator
- r: stator resistance

Synchronous generators are nonlinear electromagnetic systems. Therefore it is difficult to develop control models. In our system in which the energy is provided by flywheel, the voltage and power-distribution depend mainly on reactive power or excited power supply. At the same time the stator resistance is small and negligible. So here we suppose the following:

- the load is only reactive power
- the stator resistance is zero

Then the next equations can be reduced:

$$\frac{dE_q^{'}}{dt} = -\frac{1}{T_{do}^{'}}E_q^{'} - \frac{x_d - x_d^{'}}{T_{do}^{'}}i_d + \frac{x_{ad}}{T_{do}^{'}R_{fd}}u_{fd} \tag{3}$$

$$\frac{dE_q^{''}}{dt} = -\frac{1}{T_{do}^{''}}E_q^{''} + (\frac{1}{T_{do}^{''}} + \frac{1}{T_{do}^{'}})E_q^{'} - (\frac{x_d^{'} - x_d^{''}}{T_{do}^{''}} + \frac{x_d - x_d^{'}}{T_{do}^{'}})i_d + \frac{x_{ad}}{T_{do}^{'}R_{fd}}u_{fd}$$

Conditions for two generators connected in parallel

$$\begin{aligned} u_3 &= u_4 = u \\ i_3 + i_4 &= I \end{aligned} \tag{4}$$

and definitions for the system output

$$\begin{aligned} u &= u_3 \\ K_s &= \frac{i_4}{i_3 + i_4} \end{aligned} \tag{5}$$

leads to the following state space equation:

$$\begin{bmatrix} \frac{dE_{q3}^{'}}{dt} \\ \frac{dE_{q4}^{'}}{dt} \\ \frac{dE_{q3}^{''}}{dt} \\ \frac{dE_{q4}^{''}}{dt} \end{bmatrix} = \begin{bmatrix} 5.4e-4 & 0 & -5.3e-3 & 5.3e-3 \\ 0 & 1.0e-3 & 4.9e-3 & -4.9e-3 \\ 1.45e-2 & 0 & -4.5e-2 & 3.0e-2 \\ 0 & 4.3e-2 & 2.0e-2 & 6.3e-2 \end{bmatrix} \begin{bmatrix} E_{q3}^{'} \\ E_{q4}^{'} \\ E_{q3}^{''} \\ E_{q4}^{''} \end{bmatrix} + \begin{bmatrix} 1.2e-5 & 0 \\ 0 & 6.0e-6 \\ 1.2e-6 & 0 \\ 0 & 6.0e-6 \end{bmatrix} \begin{bmatrix} u_{f3} \\ u_{f4} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} K_s \\ u \end{bmatrix} = \begin{bmatrix} 0 & 0 & -2.63 & 2.63 \\ 0 & 0 & 2310.5 & 3751.7 \end{bmatrix} \begin{bmatrix} E'_{q3} \\ E'_{q4} \\ E''_{q3} \\ E''_{q4} \end{bmatrix}$$

3.2 Design of The Feedback Controller

The system behaviour of equation (6) is:

Eigenvalue	Damping	Freq. (rad/sec)
4.9602e-001	-1.0000e+000	4.9602e-001
-1.3468e+000	1.0000e+000	1.3468e+000
-1.8602e+001	1.0000e+000	1.8602e+001
-4.7736e+001	1.0000e+000	4.7736e+001

There is one positive eigenvalue s=0.496. Obviously the system is not stable, but this state equation has controllability and observability. We can design the optimal control systems based on quadratic performance indexes

$$J = \int_0^\infty [\xi(t) - Y(t)]^* Q[\xi(t) - Y(t)]dt + \int_0^\infty u(t)^* Ru(t)dt \tag{7}$$

According to the condition $u(t) \le u_{\max}$, minimization of J, good root-locus and fast response time , the weighting can be chosen between Q and R by some iterations.

By Matlab [4] the optimum state feedback controller can be found. At same the time, we consider the relation between state and output variables and eliminate the coupling between the variables in using integral control. The optimum controller parameters numerically calculated by means of Matlab are [5]:

Kp =		Ki =		
-4.1286e+004	3.8763e+001	-1.20e+5	100	(8)
2.5189e+004	2.6890e+001	5.00e+7	15	

The resulting closed-loop system behavior is:

Eigenvalue	Damping	Freq. (rad/sec)
-1.1240e+000+ 2.2854e+000i	4.4135e-001	2.5468e+000
-1.1240e+000- 2.2854e+000i	4.4135e-001	2.5468e+000
-8.1126e+000+ 1.7681e+001i	4.1703e-001	1.9453e+001
-8.1126e+000- 1.7681e+001i	4.1703e-001	1.9453e+001
-1.3061e+001	1.0000e+000	1.3061e+001
-3.8911e+001	1.0000e+000	3.8911e+001

Its closed-loop time response (input step function) is shown in Fig. 5.

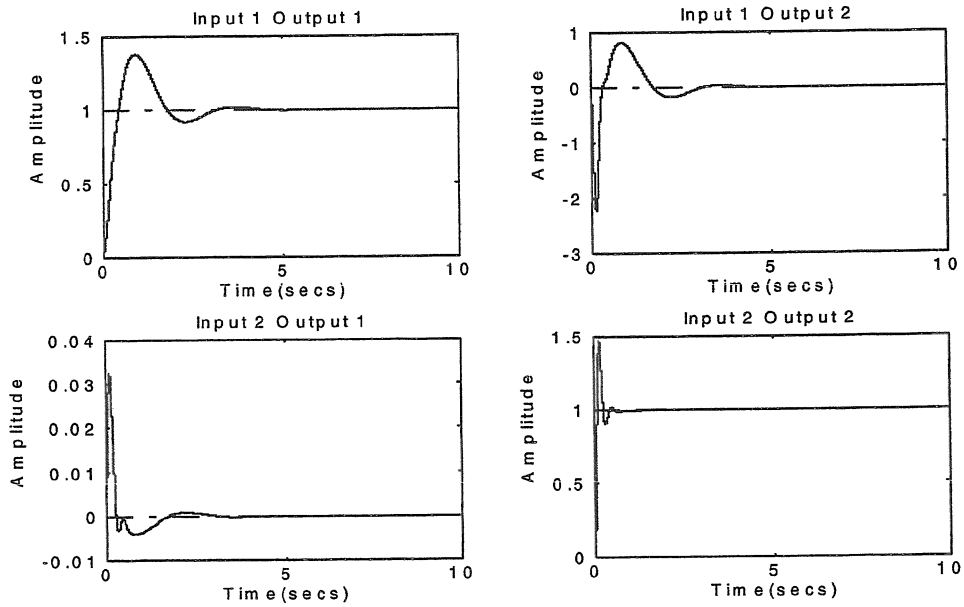


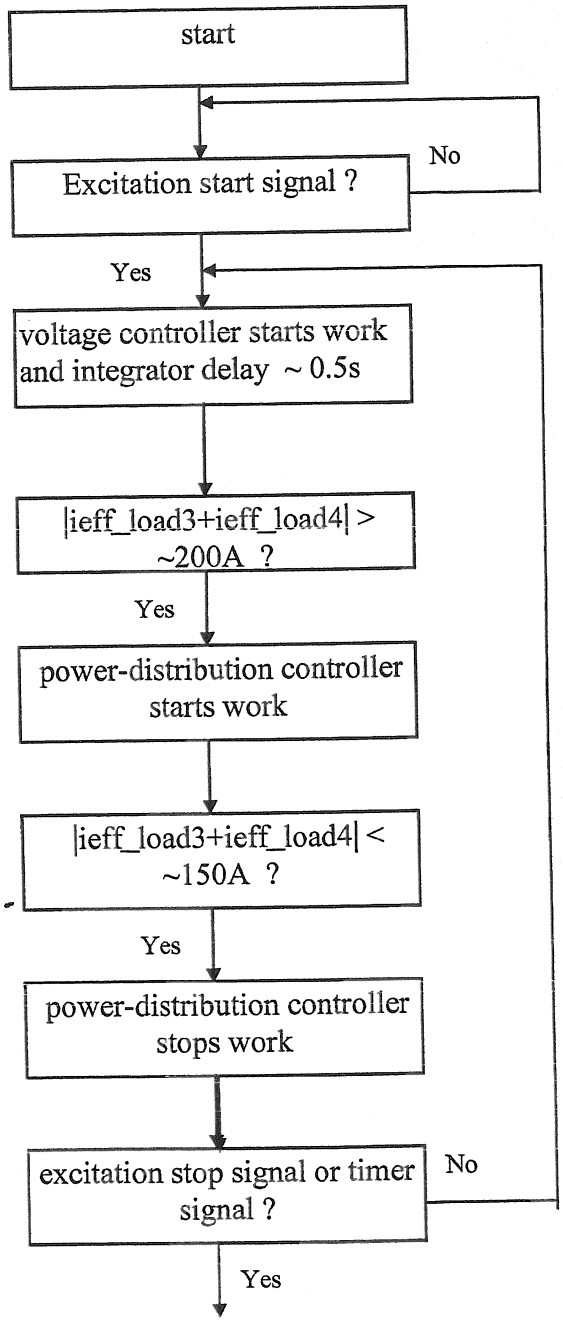
Fig. 5 The closed-loop time response using feedback controller equation (8) and a step function as input
(dashed: object value, line: real output)

The above results show that the coupling is eliminated and better control is provided.

Only minor simplifying conditions were used in designing the control model, so that there is only small difference between the control model and the real generator system. In a small range the feedback parameters were adjusted by Simplorer simulations [6] with the nonlinear generator model. Thus the following optimum feedback parameters can be found :

$$
Kp = \begin{matrix} -4.1286e{+}004 & 3.8763e{+}001 \\ 2.5189e{+}004 & 2.6890e{+}001 \end{matrix} \qquad Ki = \begin{matrix} -1.20e{+}5 & 100 \\ 1.00e{+}6 & 15 \end{matrix} \tag{9}
$$

To avoid the oscillation during the rise time of generator voltage, the integrator will not be used. The work block diagram of controller is the following:



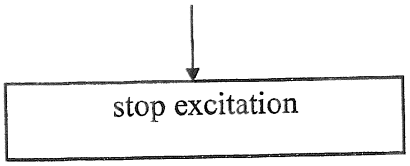


Fig.6 The controller block of the paralleled generators

4. Derivation of a Load Model

For the dynamic behavior analysis of the generators, a suitable load model must be developed. According to the feature of generator power output, the model must satisfy the following conditions :

- Not only positive reactive and active power but also negative reactive and active power can be expressed
- Fast and and high load changes can occur. It is desirable to model oscillations of the electromagnetic system, but avoid numerical oscillations during simulation.

Frequently time-varying inductors and resistors are used for load models. But this can not express the negative power, it would produce direct currents in the circuit, and it can produce errors in changing frequency. Therefore a source circuit and damping networks consisting of resistors and inductors have been used. To avoid data oscillation, a combination with constant inductance and time-varying resistance has been employed , as shown in Fig.7.

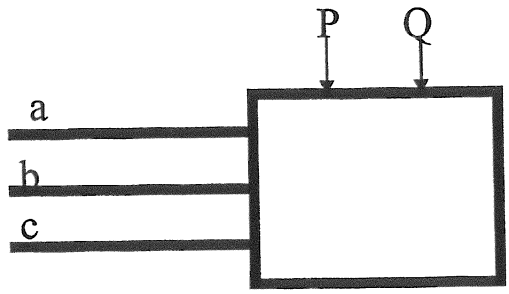


Fig. 7 (a): Principle diagram of load model

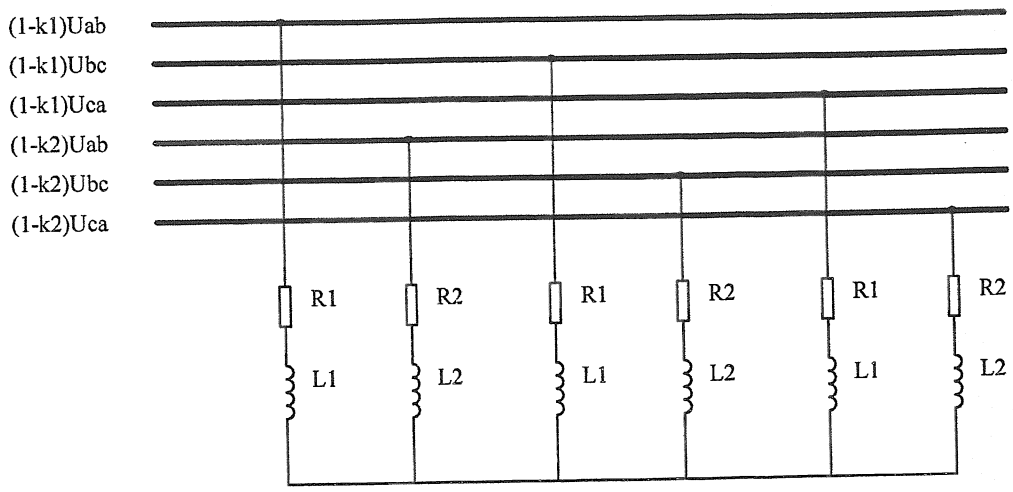


Fig. 7 (b): Load model network

The equations of the load model are :

$$
\begin{aligned}
&(1-k_1)u_a-(1-k_1)u_b-R_1 i_{1a}-L_1\frac{di_{1a}}{dt}=0\\
&(1-k_2)u_a-(1-k_2)u_b-R_2 i_{2a}-L_2\frac{di_{2a}}{dt}=0\\
&(1-k_1)u_b-(1-k_1)u_c-R_1 i_{1b}-L_1\frac{di_{1b}}{dt}=0\\
&(1-k_2)u_b-(1-k_2)u_c-R_2 i_{2b}-L_2\frac{di_{2b}}{dt}=0\\
&(1-k_1)u_c-(1-k_1)u_a-R_1 i_{1c}-L_1\frac{di_{1c}}{dt}=0\\
&(1-k_2)u_c-(1-k_2)u_a-R_2 i_{2c}-L_2\frac{di_{2c}}{dt}=0
\end{aligned}
\tag{10}
$$

This is a nonlinear equation system. L_1 , L_2 , φ_1 , φ_2 are constant; k_1, k_2, R_1, R_2 are time-varying factors. They change according to frequency and input power:

$$
\begin{aligned}
k_1 &= 1+\frac{2\pi f L_1(Q\cos\varphi_2-P\sin\varphi_2)}{3U^2\sin(\varphi_2-\varphi_1)\sin\varphi_1}\\
k_2 &= 1+\frac{2\pi f L_2(Q\cos\varphi_1-P\sin\varphi_1)}{3U^2\sin(\varphi_1-\varphi_2)\sin\varphi_2}\\
R_1 &= 2\pi f L_1 ctg\varphi_1\\
R_2 &= 2\pi f L_2 ctg\varphi_2
\end{aligned}
\tag{11}
$$

From the above equations and factors the load model was built in using the C-interface in Simplorer. The next curves are a comparison between the original power load curve (Aug#11772) and the power generated by the load model. They agree sufficiently to each other.

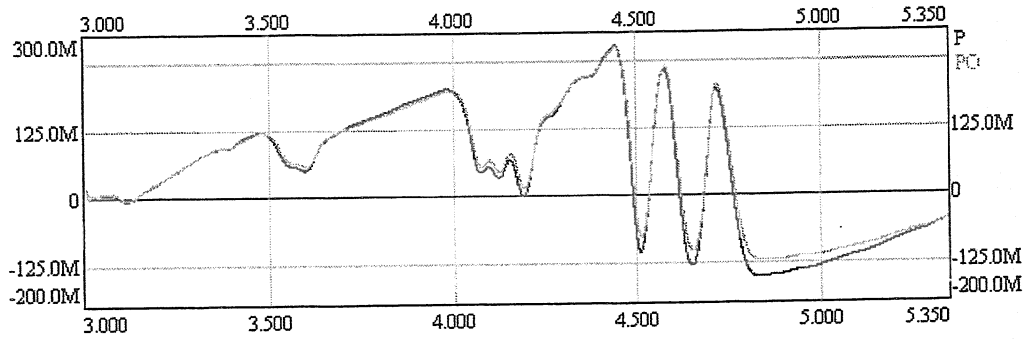


Fig.8 (a): Active input power and active output power of the load

P-- original active power (red) ; Po--- active power output from load model (gray)

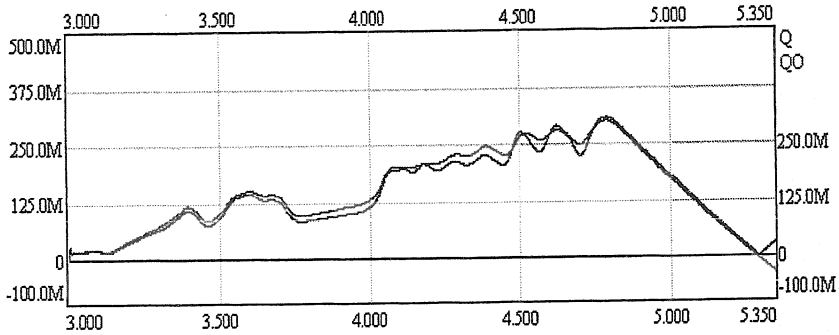


Fig.8 (b): Reactive input power and reactive output power of the load

Q-- original reactive power (red);Qo-- reactive power output from load model (green)

5. Behaviour Analysis and Results of the Paralleled Generator System with Multi-variable Control

To check the control ability of the optimized controller, we simulate its characteristics by means of the nonlinear generator models in Simplorer.

5.1 Dynamic Behavior under Extreme Load Conditions

We use the oscillation load caused by feedback control for plasma position (AUG # 11772), and extend it to the rated power of the two-generator-model. Thus the active power changes from positive to negative value with a peak-to-peak value > 300MW. This represents an extreme load condition , generally, the load curves of the generator system will be less extreme than that.

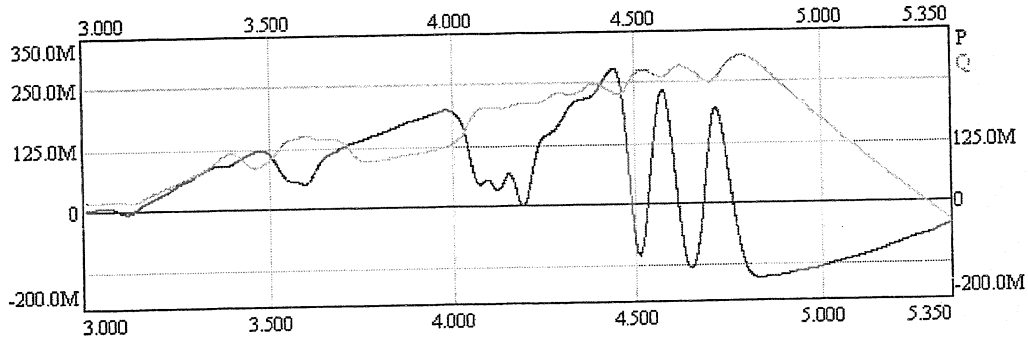


Fig. 9 (a): Load power of the parallel generators

P-- reactive power(red) , Q-- active power (grey)

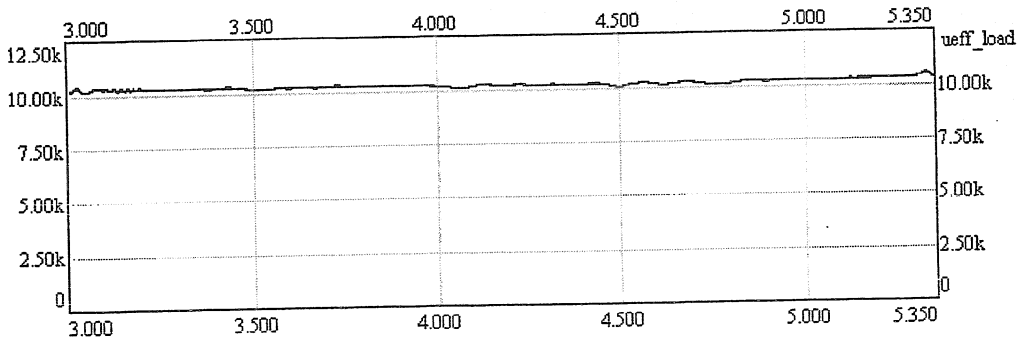


Fig. 9 (b): Busbar voltage of the generators

(ideal voltage is 10.5kV, deviation is less than 5%)

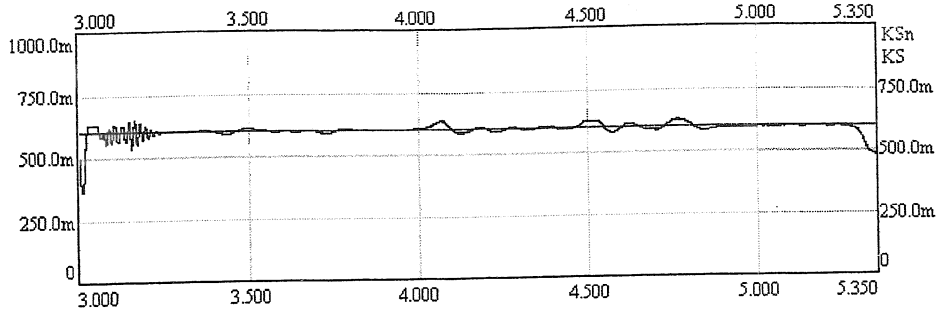


Fig. 9(c): Power-distribution between the two generators

Ksn (red)---- ideal load distribution, Ks (blue)--- real load distribution in simulation

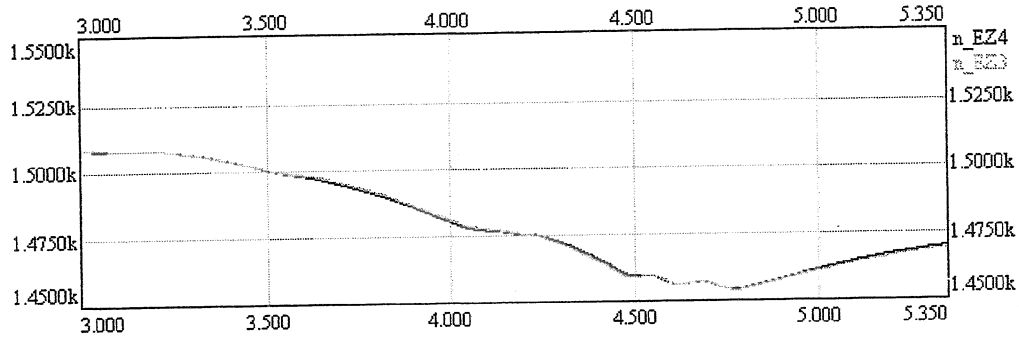


Fig. 9(d): Rotational speed of generators EZ3 and EZ4

n_EZ3(grey)---- rotational speed of generator EZ3;

n_EZ4(blue)----rotational speed of generator EZ4

5.2 Response on Sudden Load Step

Using a step function of the rated power of the two-generator-model (Pn=200MW , Qn=240MVA) , and a rise time =0.1s, the result is as shown in Fig. 10

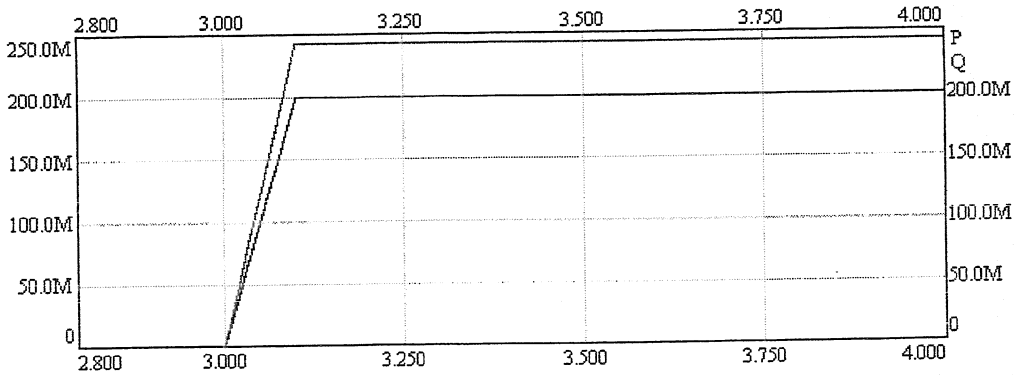


Fig. 10(a). Sudden load step: Power load

P (black)--- active power; Q (red) ---- reactive power; the rising time is 0.1s

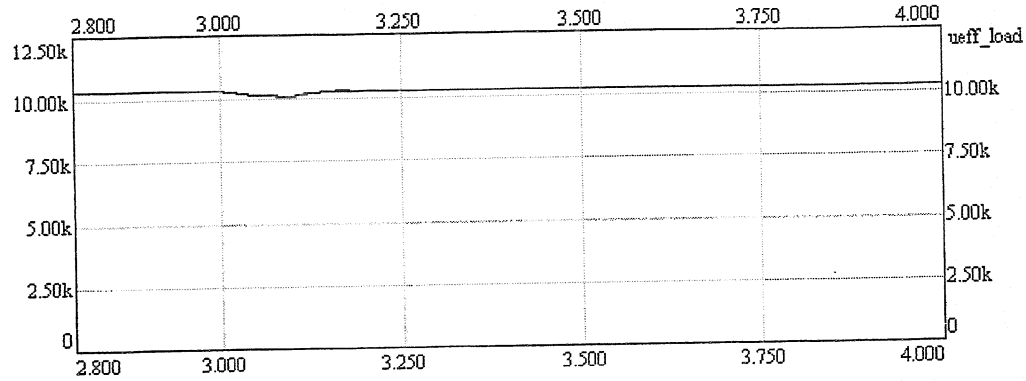


Fig. 10 (b): Busbar voltage of the paralleled generators
(the ideal voltage is 10.5 kV, the output voltage changes less than 5%)

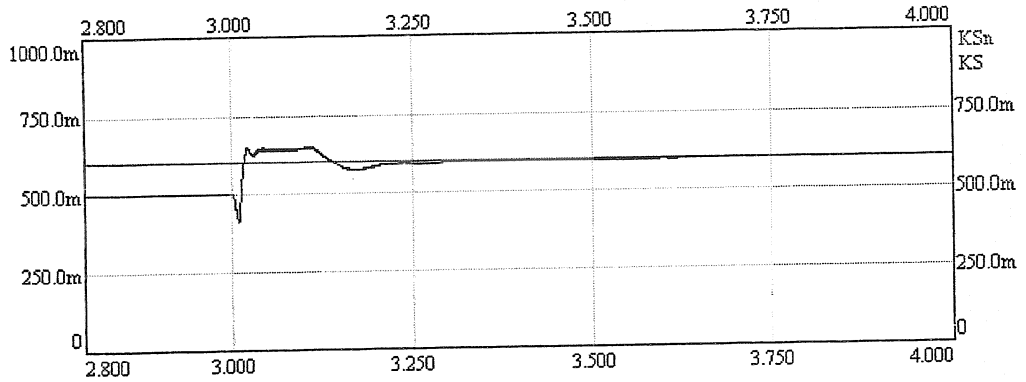


Fig. 10 (c): Power-distribution between the two generators
(Ksn (red)---- ideal value; KS (blue)---- real output value of the generators in simulation)

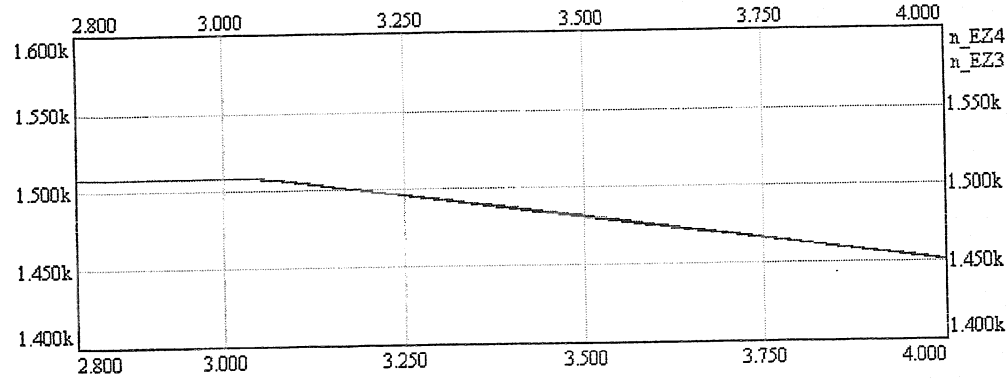


Fig. 10 (d): Rotational speed output of generators EZ3 and EZ4
(n_EZ3 (blue)---rotational speed of EZ3; n_EZ4(red)---rotational speed of EZ4; they keep consistent)

5.3 Parametrical study : Variation of generator parameters

In practice, the generator parameters are often not completely consistent with the design values or some parameters might be subject to changes (busbar inductance, cable resistance....). Therefore a good controller must have a robust characteristic.

5.3.1 Changing parameters of the generators

At first we increase the direct axis reactance of generator EZ3 by 24% and check the performance of the controller under extreme load conditions.

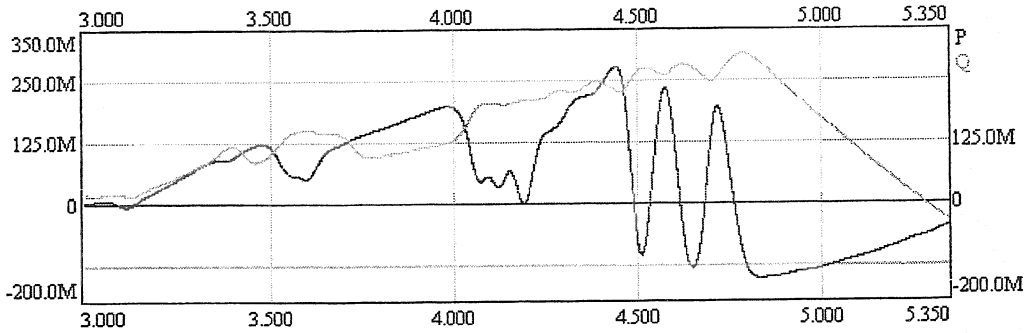


Fig. 11 (a): Power load for the paralleled generators

P-- reactive power(red) , Q-- active power (grey)

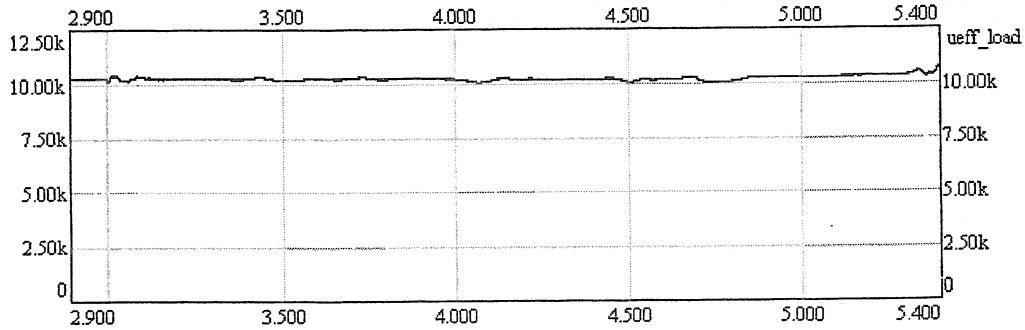


Fig. 11 (b): Busbar voltage of the paralleled generators

(ideal voltage is 10.5kV, deviation less than 5%)

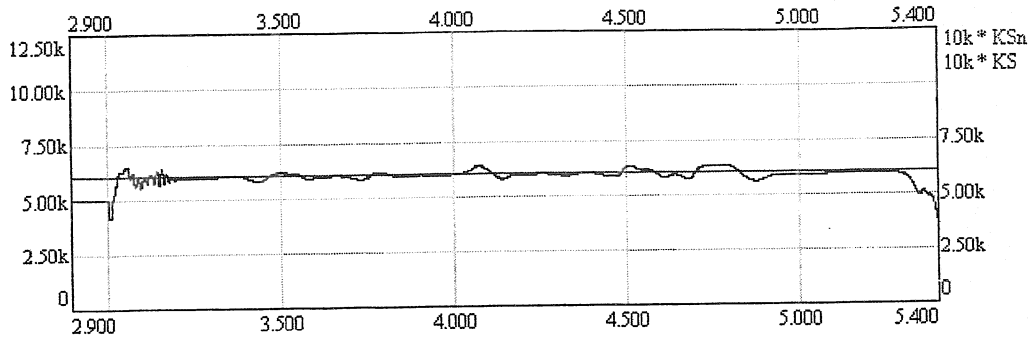


Fig. 11 (c): Power-distribution of paralleled generators (no obvious change)
Ksn (red)---- ideal load distribution, Ks (blue)--- real load distribution in simulation

The curves show that a change of that reactance shows no relevant influence in the generator control.

5.3.2 Worst case parameters of paralleled generators

Worst case parameters were derived in assuming maximum realistic tolerances of the orginal machine parameters and using the worst combination of these value. The worst parameters of the generators are shown in Table 2 .

Table 2. Worst case parameters of the flywheel generators EZ3 and EZ4

Flywheel generator	EZ3	EZ4
Synchronous reactance, direct axis (unsaturated)	4.367	4.0348
Synchronous reactance, quadrature axis (unsaturated)	2.9099	2.4148
Leakage inductance of stator winding	0.18578	0.11935
Leakage inductance of excited winding	0.70429	0.3038
Leakage inductance of damper winding	0.0584	0.13155
Staotr windding resistance	9.49×10^{-3}	6.955×10^{-3}
Excited winding resistance	2.43×10^{-3}	3.05×10^{-3}
Damper winding resistance, direct axis	8.81×10^{-3}	14.56×10^{-3}
Damper winding resistance, quadrature axis	18.924×10^{-3}	31.96×10^{-3}

Note: The worst case parameters were derived from the original parameters as follows:

$Ls=1.4Ls$; $Rs=1.3Rs$; $R_{kq}=2R_{kq}$

The behaviour of the rotor angle versus frequency at paralleled generators can be calculated by using torques with different

frequencies in each simulation (sine function, amplitude 10^5Nm), as shown in Table 3.

Table 3 Rotor angle calculated in using torques with different frequencies at EZ3 (sine function, amplitude 10^5Nm)

torque frequence (HZ)	rotor angle (Deg.)			
	orginal parameters		modified parameters	
	EZ3	EZ4	EZ3	EZ4
0.007	9.43	5.25	9.62	5.49
0.01	9.60	5.62	9.79	5.66
0.015	9.98	5.66	9.98	5.66
0.02	9.79	5.66	9.98	5.85
0.03	9.62	5.25	10.20	5.66
0.045	9.26	5.66	10.42	5.65
0.05	9.26	5.66	10.52	5.98
0.072	8.91	5.66	11.31	6.57
0.08	8.88	5.98	11.55	6.69
0.085	8.71	5.98	11.96	6.92
0.09	8.70	6.05	13.04	7.28
0.1	8.59	6.05	12.49	8.19
0.15	7.24	5.62	14.69	9.97
0.18	5.98	5.06	12.69	9.07
0.2	5.56	4.83	10.69	7.43
0.25	3.90	3.42	5.67	4.10
0.3	2.85	2.73	3.62	2.89
0.5	1.11	0.99	1.14	0.96
1.0	0.37	0.37	0.39	0.31
2.0	0.20	0.20	0.20	0.20

From that behaviour, as shown in Fig. 12 , the resonant frequency is 0.18Hz. Worst case parameter results were used for illustration of the natural frequency in Fig. 12 (a). A comparison with simulation results using the original machine parameters is given in Fig. 12 (b) for EZ3 and 12 (c) for EZ4.

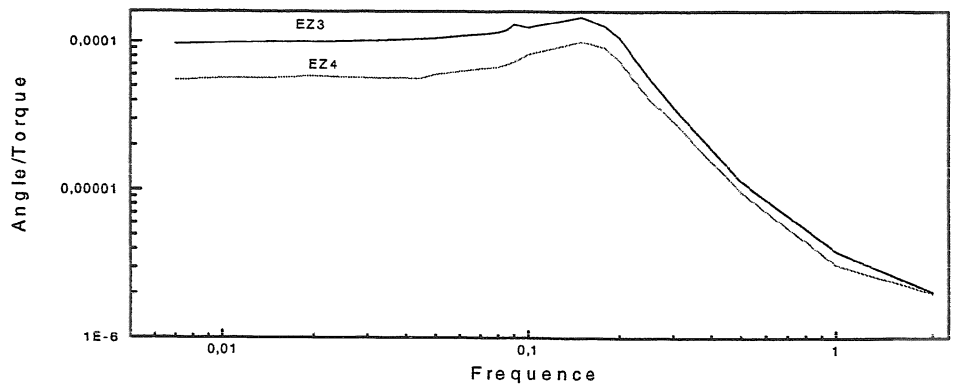


Fig. 12 (a) Behaviour of EZ3 and EZ4: Rotor angle / input torque (using the worst parameters of the generators)

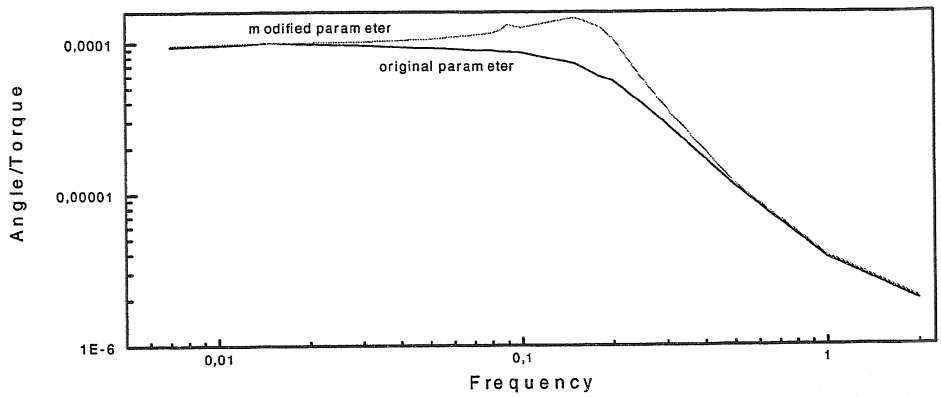


Fig. 12 (b) Behaviour of EZ3 rotor angle / input torque (using the worst and original parameters of the generators)

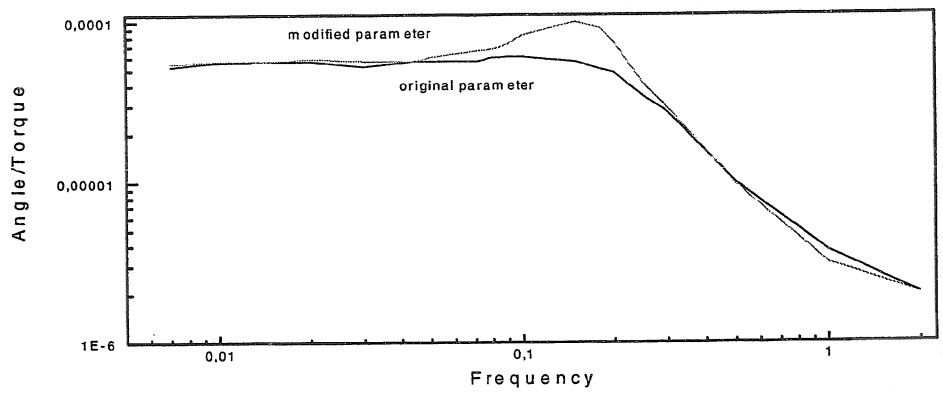


Fig. 12 (c) Behaviour of EZ4 rotor angle / input torque (using the worst and original parameters of the generators)

Simulation of extreme load case with worst machine parameters (see Table 2):

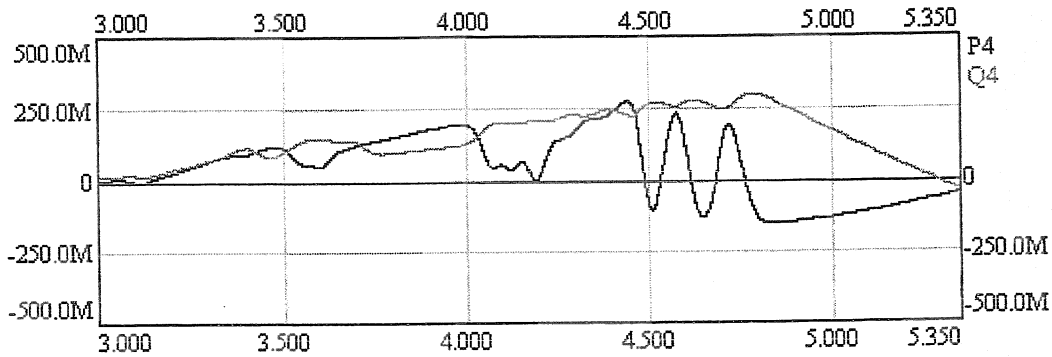


Fig. 13 (a): Power load for the paralleled generators

P-- reactive power(red) , Q-- active power (grey)

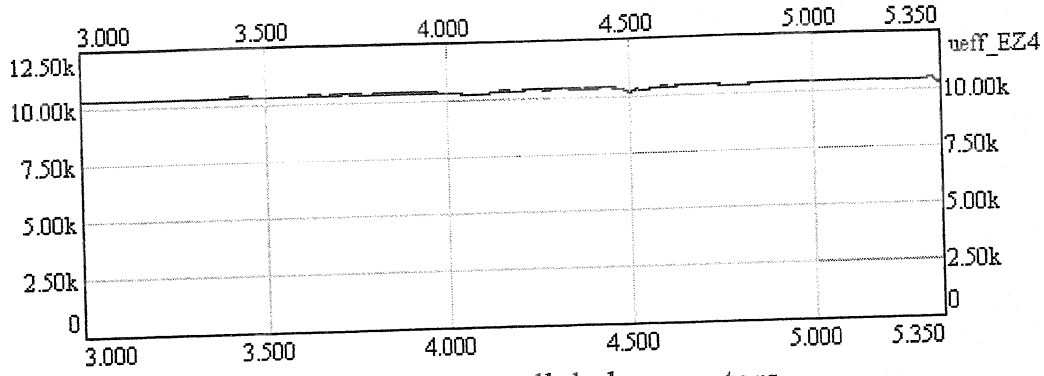


Fig. 13 (b): Busbar voltage of the paralleled generators
(ideal voltage is 10.5kV, deviation less than 5%)

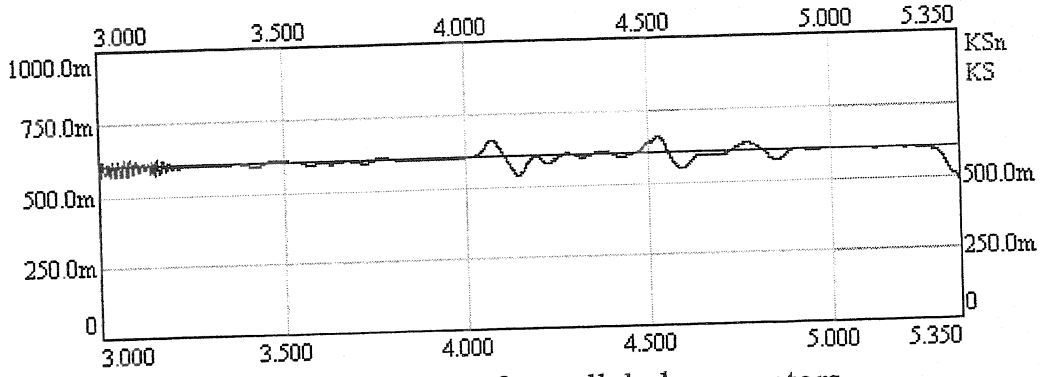


Fig. 13 (c): Power-distribution of paralleled generators
Ksn (green)---- ideal load distribution, Ks (red)--- real load distribution in simulation
(there is some change than using original generator parameters, but it is acceptable)

5.4 Circular current

In a paralleled generator system , the circular current can decrease the power output of the system, in serious cases circular currents can produce oscillations in the generator system and cause a tripping of the protection system. A good controller must keep the circular current zero. In practise that requirement means that the circular current must be very small under two cases: load and no load, as shown in Figures 14 (a) and 14 (b).

In the case of no load, the two generators are paralleled at t=1.4s, the system produces a circular current, but the system reaches quickly its balance and keeps the current zero (shown in Fig. 14 (a)).
In the case of load, the two generators are paralleled at t=1.4s, the system produces an initial circular current, but the circular current

decreases to zero very quickly. Especially under load, there is no circular current (see Fig. 14 (b)).

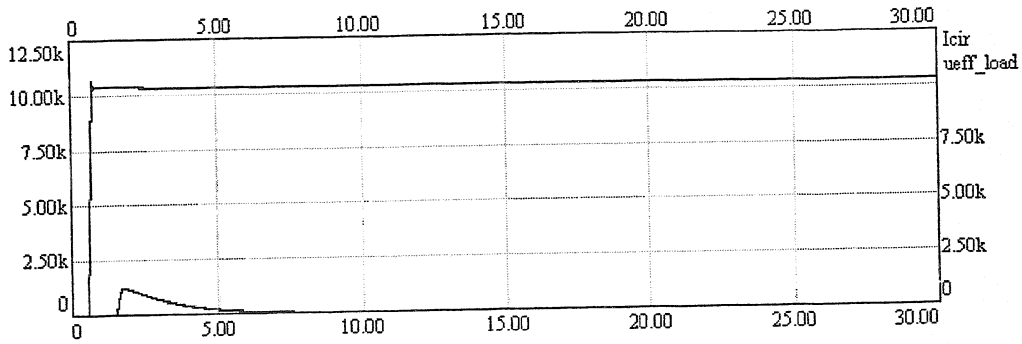


Fig. 14 (a) Voltage and circular current at no-load

ueff_load (black)---- busbar voltage; Icir (blue)---- circular current

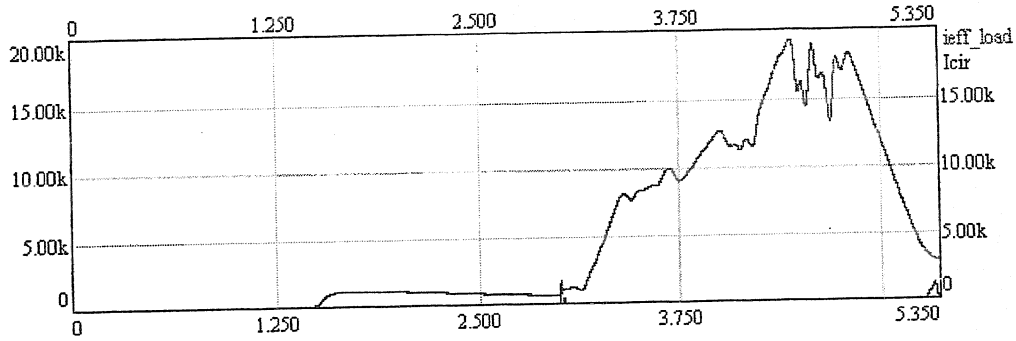


Fig. 14 (b) load current and circular current at extreme load (as shown in Fig.13(a))

ieff_load (red)---- load current; Icir (blue)---- circular current; Icir is zero during load.

5.5 Operational region of the power factor in the paralleled generator system

The active power is supplied by the flywheels of the generators, the reactive power is controlled by the excitation of the two machines. A defined reactive power is the necessary condition for the paralleled generator system. In static operation of the paralleled generator system, the condition can be derived by equation (12):

(12)

or

$$-0.98 \leq \cos\varphi \leq 0.98 \qquad (13)$$

The behaviour of the generators in case of a high power factor is shown in Figs. 15 (a) and (b).

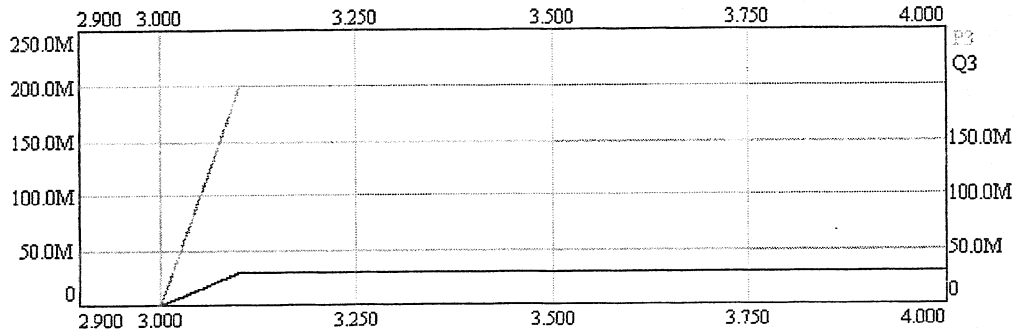


Fig.15 (a) Total load power (power factor is 0.98)

P3---active power , Q3---reactive power

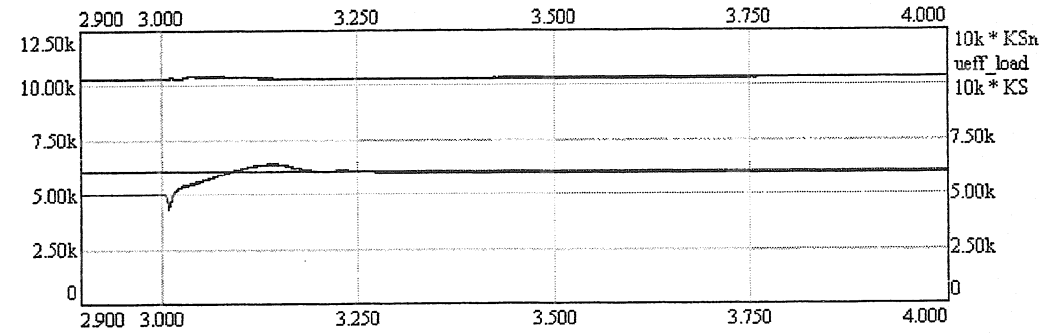


Fig.15(b) Busbar voltage and power distribution of paralleled generators

ueff-load (black)--- voltage; Ksn (red)---- ideal load distribution, Ks (blue)--- real load distribution in simulation

In case of dynamic loads, because of the quite different parameters of the two generators, their dynamic rotor angle can not be kept in accordance at all times. The dynamic behaviour depends on the change rate of load and the generator parameters. This is being considered in modifying the parameter $k_{jn} := k_{jn}+10\%$. The dynamic power factor range can be received from above equations:

$$\cos\varphi < 0.944$$

This result can be validated by simulations, as shown in Fig. 16.

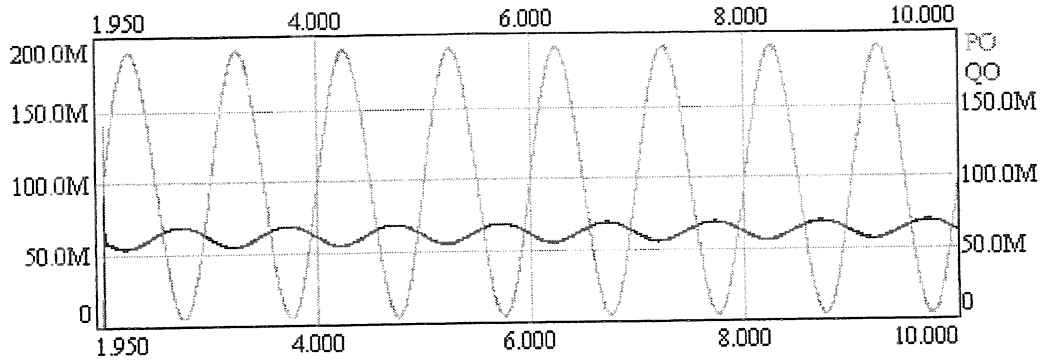


Fig. 16 (a) Total load power (power factor is less than 0.94)

P0(grey)---active power , Q0(green)---reactive power

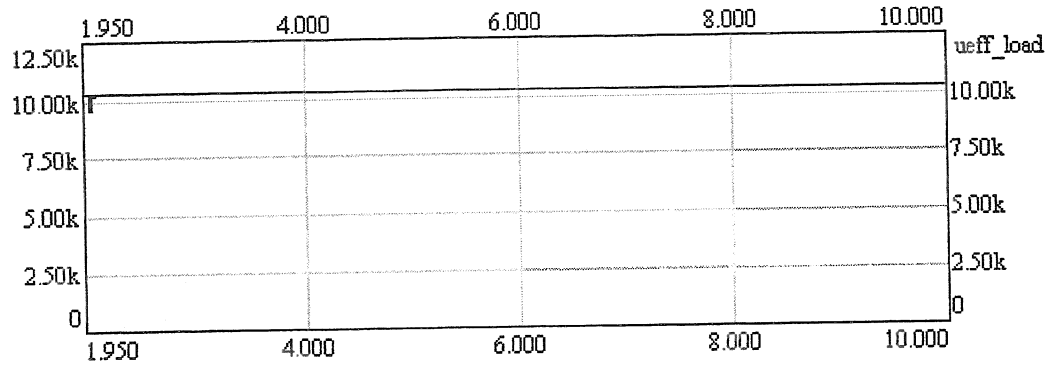


Fig.16 (b) Busbar voltage of paralleled generators

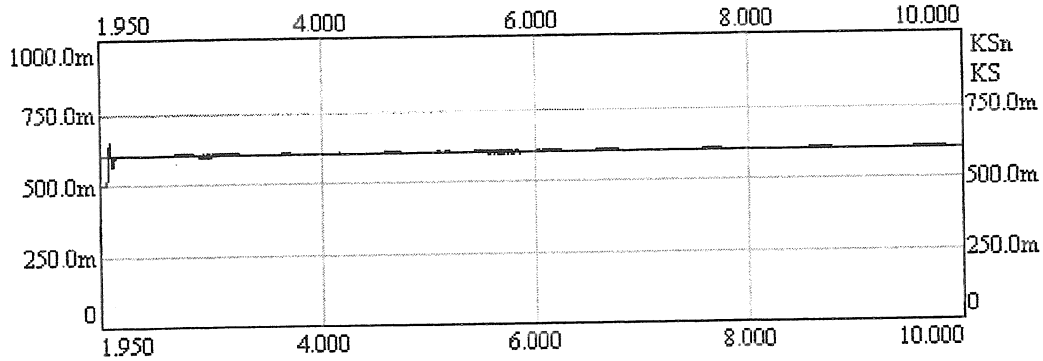


Fig.16 (c) Power distribution of paralleled generators

Ksn (red)---- ideal load distribution, Ks (blue)--- real load distribution in simulation

6. Conclusion

The paralleling of the two 10.5kV – 100Hz networks has distinct advantages for the future development of ASDEX-Upgrade, if only by solving two major problems:

- Optimisation of the **power** loading between the two generators, this function being achieved by the voltage / power controller

- Optimisation of the **energy** loading between the two generators, by the fact of having a single system frequency

The numerical simulations performed demonstrate that these problems can be solved by the multi-variable controller presented in Chapter 3. In contrast to the more conventional controller types that were investigated before (see Chapter 1), one of the main advantages of the multi-variable controller is its robustness against external disturbances (variation of machine parameters, harmonics, EMC problems).

However, as any new system attempting to solve existing problems, the implementation of a multi-variable controller in the existing generator control system will introduce its own new problems. The purpose of the conceptual studies in Chapter 5 and Appendix 2 was to provide a broad review of a range of issues associated with such a project. It is by no means an extensive survey.

At this stage, the conclusion of the conceptual studies is that the project is a viable proposition though difficulties are expected. Further progress requires the intervention of Industry to prepare a detailed scheme so that the technical realisation of paralleling the flywheel generators EZ3 and EZ4 can be prepared.

7. References

[1] V. Landenberger, "Modellierung von Betriebsmitteln und Untersuchung ihres transienten elektromagnetischen und elektromechanischen Verhaltens", Studienarbeit, Universität Karlsruhe, 1998, unpublished

[2] A. M. Miri, V. Landenberger, C. Sihler, B. Streibl, "Transient Behaviour of Two Parallel Connected Flywheel Generators During Pulsed Power Operation", Proc. Int. Conf. Power System Transients (IPST), Budapest, Hungary, 1999, pp. 307-312

[3] V. Landenberger, "Statische und transiente Stabilität zweier parallel geschalteter Schwungmasse-Synchrongeneratoren zur Erzeugung hoher Stoßleistung", Diplomarbeit, Universität Karlsruhe, 1999, unpublished

[4] The Math Works Inc., "MATLAB – High-Performance numeric computation and visualization software", Version 4.0, 1993

[5] W. Treutterer, personal communication, IPP, 1999

[6] SIMEC GmbH, "Simplorer", Version 4.0, Chemnitz, 1998

Appendix 1. VC++ Source Program of Load model in C-interface of Simplorer

```
// --------- Load Model Expressed by Triangle ------------------
//#include "stdafx.h"
#include <windows.h>
#include <assert.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "Udmusr.h"
// CallBack function
LIBERRPROC        pfuError;
LIBBACKPROC pfuCallBack;
// Default parameters
double L1=1.0e-3;
double L2=1.0e-3;
double Pi=3.14159265359;
// Parameter set
typedef struct  {        EXTVAR un;
            EXTVAR frequence;
                                    EXTVAR pload;        // Load P-power (if any)
                                    EXTVAR qload;        // Load Q (if any)
                              } PARAMETERS;
// DLL init function for example DC machine model
extern "C" UDMRET __declspec( dllexport ) UDMInit( LIBERRPROC errProc,
LIBBACKPROC cbProc, UDMINFO *udmInfo )
{
        pfuError          = errProc;                    // Error function
        pfuCallBack  = cbProc;                          // CallBack function
        (*udmInfo)[0] = UDMOBJTYPE_UDC;        // Object type: user-defined model
        (*udmInfo)[1] = sizeof(PARAMETERS);  // Component parameters
        (*udmInfo)[2] = 0;                                    // unused for UDC's
        return 0;
}

// DLL main function
extern "C" UDMRET __declspec( dllexport ) UDMMain( UDMCALLFCT function,
UDMSPARA pstr, UDMLPARA pir, UDMLPARA por, UDMDATA hInstData, UDMDATA
hDefData )
{
        char            *pch1, *pch2;
        char            *pUDCVec1, *pUDCVec2;
        double          Un,F,Pload,Qload;
        double          dIn[2], dOut[2];
        double          *pIn = dIn, *pOut = dOut;
        USHRT                   iCnt;
        UDMRET                  iRet = 0;
```

```
        UDCDATA             *pUDCData;
        PARAMETERS          *datPar;
        // Access object data
        if( hInstData == (UDMDATA)0 )
                return MSG_UDMINVARG;
        if( hDefData  == (UDMDATA)0 )
                return MSG_UDMINVARG;
        datPar = (PARAMETERS *)gLock( hInstData );
        if( !datPar )
                return MSG_GLOBLOCK;
        pUDCData = (UDCDATA *)gLock( hDefData );
        if( !pUDCData )
        {
                gUnlock( hInstData );
                return MSG_GLOBLOCK;
        }

        // Function distributor
    switch( function )
        {
                case UCF_DUMMY:
                                                        break;
                case UCF_OPEN:
                                                        // Initialization with default values
memset( &(datPar->un), 0, sizeof(EXTVAR) );
memset( &(datPar->frequence), 0, sizeof(EXTVAR) );
memset( &(datPar->pload), 0, sizeof(EXTVAR) );
memset( &(datPar->qload), 0, sizeof(EXTVAR) );
// Processing the parameter string: character "," is separator
for ( iCnt = 0, pch1 = pstr; pch1; iCnt++ )
{
if( (pch2 = strchr( pch1, ',' )) != NULL )
        *pch2 = 0;
        if( *pch1 )
        switch( iCnt )
        {
case 0  : strcpy( datPar->un.name, pch1 ); break;
case 1  : strcpy( datPar->frequence.name, pch1 ); break;
case 2  : strcpy( datPar->pload.name, pch1 ); break;
case 3  : strcpy( datPar->qload.name, pch1 ); break;
        }
pch1 = (pch2) ? pch2+1 : NULL;
                                                        }
// Determine system dimensions
pUDCData->states    = 6;
pUDCData->entries   = 36;
pUDCData->stores    = 0;
// Error message if too much parameters have been specified
if( iCnt>4 )
pfuError( WARN_ID, "Too much parameters in model definition!" );
```

```
break;

case UCF_INITIALIZE:
// Resolving external frequence and load torque
if( *(datPar->un.name) )
{
if( pfuCallBack( UBF_IMPORT, datPar->un.name, (UDMLPARA)0, (UDMLPARA)pOut )
== 0 )
{
datPar->un.v.flag = 1;
datPar->un.v.ind1 = (int)dOut[0];
datPar->un.v.ind2 = (int)dOut[1];
                                                    }
                                                }
                //*****

if( *(datPar->frequence.name) )
{
if( pfuCallBack( UBF_IMPORT, datPar->frequence.name, (UDMLPARA)0,
(UDMLPARA)pOut ) == 0 )
{
datPar->frequence.v.flag = 1;
datPar->frequence.v.ind1 = (int)dOut[0];
datPar->frequence.v.ind2 = (int)dOut[1];
}
}
                //*****
if( *(datPar->pload.name) )
{
if( pfuCallBack( UBF_IMPORT, datPar->pload.name, (UDMLPARA)0, (UDMLPARA)pOut
) == 0 )
{
datPar->pload.v.flag = 1;
datPar->pload.v.ind1 = (int)dOut[0];
datPar->pload.v.ind2 = (int)dOut[1];
}
}
                                                    //*****
if( *(datPar->qload.name) )
{
if( pfuCallBack( UBF_IMPORT, datPar->qload.name, (UDMLPARA)0, (UDMLPARA)pOut
) == 0 )
{
datPar->qload.v.flag = 1;
datPar->qload.v.ind1 = (int)dOut[0];
datPar->qload.v.ind2 = (int)dOut[1];
}
}

// Locking vector 2
```

```
if( pUDCData->vector2 )
{
if( (pUDCVec2 = (char *)gLock( pUDCData->vector2 )) != NULL )
{
// Determine sequence of Jacobian matrix entries

(UDCRow)[0] = 0; (UDCCol)[0] = 3;
(UDCRow)[1] = 0; (UDCCol)[1] = 5;
(UDCRow)[2] = 0; (UDCCol)[2] = 6;
 (UDCRow)[3] = 0; (UDCCol)[3] = 8;

 (UDCRow)[4] = 1; (UDCCol)[4] = 3;
 (UDCRow)[5] = 1; (UDCCol)[5] = 4;
 (UDCRow)[6] = 1; (UDCCol)[6] = 6;
 (UDCRow)[7] = 1; (UDCCol)[7] = 7;
 (UDCRow)[8] = 2; (UDCCol)[8] = 4;
 (UDCRow)[9] = 2; (UDCCol)[9] = 5;
 (UDCRow)[10] = 2; (UDCCol)[10] =7;
 (UDCRow)[11] = 2; (UDCCol)[11] =8;

 (UDCRow)[12] = 3; (UDCCol)[12] = 0;
 (UDCRow)[13] = 3; (UDCCol)[13] =1;
(UDCRow)[14] = 4; (UDCCol)[14] =1;
 (UDCRow)[15] = 4; (UDCCol)[15] = 2;

 (UDCRow)[16] = 5; (UDCCol)[16] = 0;
 (UDCRow)[17] = 5; (UDCCol)[17] = 2;
 (UDCRow)[18] = 6; (UDCCol)[18] = 0;
 (UDCRow)[19] = 6; (UDCCol)[19] = 1;

 (UDCRow)[20] = 7; (UDCCol)[20] = 1;
(UDCRow)[21] = 7; (UDCCol)[21] = 2;
(UDCRow)[22] = 8; (UDCCol)[22] = 0;
 (UDCRow)[23] = 8; (UDCCol)[23] = 2;
 (UDCRow)[24] = 3; (UDCCol)[24] = 3;
 (UDCRow)[25] = 4; (UDCCol)[25] = 4;
 (UDCRow)[26] = 5; (UDCCol)[26] = 5;
(UDCRow)[27] = 6; (UDCCol)[27] = 6;
(UDCRow)[28] = 7; (UDCCol)[28] = 7;
 (UDCRow)[29] = 8; (UDCCol)[29] = 8;

 (UDCRow)[30] = 3; (UDCCol)[30] = 3;
(UDCRow)[31] = 4; (UDCCol)[31] = 4;
 (UDCRow)[32] = 5; (UDCCol)[32] = 5;
 (UDCRow)[33] = 6; (UDCCol)[33] = 6;
 (UDCRow)[34] = 7; (UDCCol)[34] = 7;
 (UDCRow)[35] = 8; (UDCCol)[35] = 8;

 // Setting differentiation flags
 (UDCFlag)[30] |=D_DT_OPERAT;
```

```
 (UDCFlag)[31] |=D_DT_OPERAT;
(UDCFlag)[32] |=D_DT_OPERAT;
 (UDCFlag)[33] |=D_DT_OPERAT;
 (UDCFlag)[34] |=D_DT_OPERAT;
 (UDCFlag)[35] |=D_DT_OPERAT;

// Fill constant Jacobian matrix entries
 (UDCJaco)[0] =        1.0;
 (UDCJaco)[1] =  -1.0;
 (UDCJaco)[2] =        1.0;
 (UDCJaco)[3] = -1.0;
(UDCJaco)[4] = -1.0;
 (UDCJaco)[5] = 1.0;

(UDCJaco)[6] = -1.0;
(UDCJaco)[7] = 1.0;
(UDCJaco)[8] = -1.0;
 (UDCJaco)[9] = 1.0;
 (UDCJaco)[10] = -1.0;
 (UDCJaco)[11] = 1.0;

// Unlocking vector 2
gUnlock( pUDCData->vector2 );
// Error messages
}
else
iRet = MSG_GLOBLOCK;
}
else
iRet = MSG_UDMINVARG;
break;
case UCF_SIMULATE:
//* import noimal voltage
Un= 0.0;
if( datPar->un.v.flag )
{
dIn[0] = (double)datPar->un.v.ind1;
dIn[1] = (double)datPar->un.v.ind2;
iRet=pfuCallBack( UBF_GET, (UDMSPARA)0, (UDMLPARA)pIn, (UDMLPARA)pOut );
if( !iRet )
{
Un =datPar->un.v.value = dOut[0];
                                                    }
                                                }
        //*** import external frequence

F= 0.0;
if( datPar->frequence.v.flag )
{
dIn[0] = (double)datPar->frequence.v.ind1;
```

```
dIn[1] = (double)datPar->frequence.v.ind2;
iRet=pfuCallBack( UBF_GET, (UDMSPARA)0, (UDMLPARA)pIn, (UDMLPARA)pOut );
if( !iRet )
{
F =datPar->frequence.v.value = dOut[0];
                                                    }
                                                }

// Importing external load power
Pload = 0.0;
if( datPar->pload.v.flag )
                                                    {
dIn[0] = (double)datPar->pload.v.ind1;dIn[1] = (double)datPar->pload.v.ind2;
iRet=pfuCallBack( UBF_GET, (UDMSPARA)0, (UDMLPARA)pIn, (UDMLPARA)pOut );
if( !iRet )
{
Pload =datPar->pload.v.value = dOut[0];
                                                    }
                                                }
                //****
Qload = 0.0;
if( datPar->qload.v.flag )
                                                    {
dIn[0] = (double)datPar->qload.v.ind1;
dIn[1] = (double)datPar->qload.v.ind2;

iRet=pfuCallBack( UBF_GET, (UDMSPARA)0, (UDMLPARA)pIn, (UDMLPARA)pOut );
if( !iRet )
        {
Qload =datPar->qload.v.value = dOut[0];
}
        }


// Locking vectors
if( pUDCData->vector1 && pUDCData->vector2 )
{
if( (pUDCVec1 = (char *)gLock( pUDCData->vector1 )) != NULL && (pUDCVec2 = (char
*)gLock( pUDCData->vector2 )) != NULL )
        {
          // calcuate  factor
  double    UU=0.0001+((double)datPar->un.v.value);
double    FF=0.00001+((double)datPar->frequence.v.value);
double    X1=2.0*Pi*fabs(FF)*L1;
double    X2=2.0*Pi*fabs(FF)*L2;
double    R1=X1/sqrt(10.0);   //*** set up factor about resistance and inductance
double    R2=X2/sqrt(4.0);//**
double    D1=atan(X1/R1);
double    D2=atan(X2/R2);
double    P=((double)datPar->pload.v.value);
double    Q=((double)datPar->qload.v.value);
```

```
double    P1=-(Q-P*tan(D2))/(tan(D2)-tan(D1));
double    P2=(Q-P*tan(D1))/(tan(D2)-tan(D1));

double   K1=1-P1*sqrt(R1*R1+X1*X1)/(3.0*UU*UU*cos(D1)); //** branch 1 factor
double    K2=1-P2*sqrt(R2*R2+X2*X2)/(3.0*UU*UU*cos(D2));  // **branch 2 factor

// Fill (dynamic parts of) Jacobian matrix
(UDCJaco)[24] =      -R1;
 (UDCJaco)[25] = -R1;
                        (UDCJaco)[26] =      -R1;
                        (UDCJaco)[27] =      -R2;
                         (UDCJaco)[28] = -R2;
                        (UDCJaco)[29] =      -R2;
                        (UDCJaco)[12] =      1.0-K1;
                         (UDCJaco)[13] = -(1.0-K1);
                         (UDCJaco)[14] = 1.0-K1;
                         (UDCJaco)[15] =      -(1.0-K1);
                         (UDCJaco)[16] = -(1.0-K1);
                         (UDCJaco)[17] = (1.0-K1);
                         (UDCJaco)[18] =      (1.0-K2);
                         (UDCJaco)[19] = -(1.0-K2);
                         (UDCJaco)[20] = (1.0-K2);
                         (UDCJaco)[21] =      -(1.0-K2);
                         (UDCJaco)[22] = -(1.0-K2);
                         (UDCJaco)[23] = (1.0-K2);
                         (UDCJaco)[30] =      -L1*ISI_DHB;
                         (UDCJaco)[31] =      -L1*ISI_DHB;
                         (UDCJaco)[32] =      -L1*ISI_DHB;
                         (UDCJaco)[33] =      -L2*ISI_DHB;
                         (UDCJaco)[34] =      -L2*ISI_DHB;
                         (UDCJaco)[35] =      -L2*ISI_DHB;

                        // Fill right side vector
                         (UDCDrs)[0] = 0.0;
                         (UDCDrs)[1] = 0.0;
                         (UDCDrs)[2] = 0.0;
                        (UDCDrs)[3] = 0.0;
                         (UDCDrs)[4] = 0.0;
                         (UDCDrs)[5] = 0.0;
                         (UDCDrs)[6] = 0.0;
                         (UDCDrs)[7] = 0.0;
                         (UDCDrs)[8] = 0.0;
                        // Unlocking vectors
 gUnlock( pUDCData->vector2 );      gUnlock( pUDCData->vector1 );

                        // Error messages
        }
else
iRet = MSG_GLOBLOCK;
        }
```

```
else
iRet = MSG_UDMINVARG;
break;
case UCF_VALIDATE:
break;
case UCF_EXPORT:
// Providing the indexes of the exported quantities (formal)
iCnt = 0;
if( !strcmp( strupr( pstr ), "U" ) ) iCnt = 1; // voltage
if( !strcmp( strupr( pstr ), "I" ) ) iCnt = 2; // current

OEX_INDEX = (double)iCnt;
break;
case UCF_PUT:
// Locking vector 1
if( pUDCData->vector1 )
{
if( (pUDCVec1 = (char *)gLock( pUDCData->vector1 )) != NULL )
{
// Providing the present values of the exported quantities (actual)
iCnt = (int)IPU_INDEX; OPU_VALUE = 0.0;
switch( iCnt )
{
case 1: OPU_VALUE = (UDCDu )[0] - *(UDCDu+3); break;
case 2: OPU_VALUE = (UDCDu )[4] ;          break;
}

// Unlocking vector 1
gUnlock( pUDCData->vector1 );
// Error messages
if( iCnt<1 || iCnt>2 )
iRet = MSG_UDMCORRUPT;
}
else
iRet = MSG_GLOBLOCK;
}
else
iRet = MSG_UDMINVARG;
break;
case UCF_CLOSE:
break;
        }
// Release object data and return result
gUnlock( hDefData ); gUnlock( hInstData );
return iRet;
}


NodeInfo gNodeInfo;
extern "C" long __declspec( dllexport ) GetVersionNumber( void )
```

```
{
        return _UDX_VERSION_;
}
// Informationen über das Modell an die grafische Oberfläche
extern "C" __declspec( dllexport ) NodeInfo *ListNodeInfo( long lIndex )
{
        switch( lIndex )
        {
                ////////////////////////////////////////////
                // AUSGABEN
//              case 0: strcpy(gNodeInfo.m_Name, "U" ); // voltage
//                              gNodeInfo.m_Type = Output;
//                              break;
//              case 1: strcpy(gNodeInfo.m_Name, "I" ); // current
//                              gNodeInfo.m_Type = Output;
//                              break;

// PARAMETER
case 0: strcpy(gNodeInfo.m_Name, "Un" );
        gNodeInfo.m_Type = Parameter;
        break;
case 1: strcpy(gNodeInfo.m_Name, "Frequence" );
        gNodeInfo.m_Type = Parameter;
        break;

case 2:strcpy(gNodeInfo.m_Name, "Pload" );
        gNodeInfo.m_Type = Parameter;
        break;
case 3:strcpy(gNodeInfo.m_Name, "Qload" );
        gNodeInfo.m_Type = Parameter;
        break;
                ////////////////////////////////////////////
                // ELECTRICAL NODES
case 4:strcpy(gNodeInfo.m_Name, "K1" );
        gNodeInfo.m_Type = ConnectCircuit;
        break;
case 5:strcpy(gNodeInfo.m_Name, "K2" );
        gNodeInfo.m_Type = ConnectCircuit;
        break;
case 6:strcpy(gNodeInfo.m_Name, "K3" );
        gNodeInfo.m_Type = ConnectCircuit;
        break;
                default:
                        return NULL;
        }

        return &gNodeInfo;
}
```

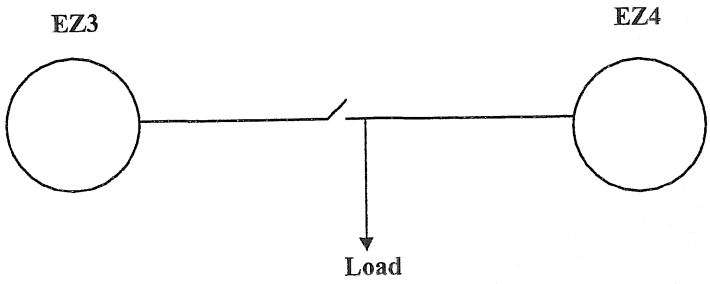
Appendix 2. Summary of Simulation Results

Overview on the summary of simulation results:

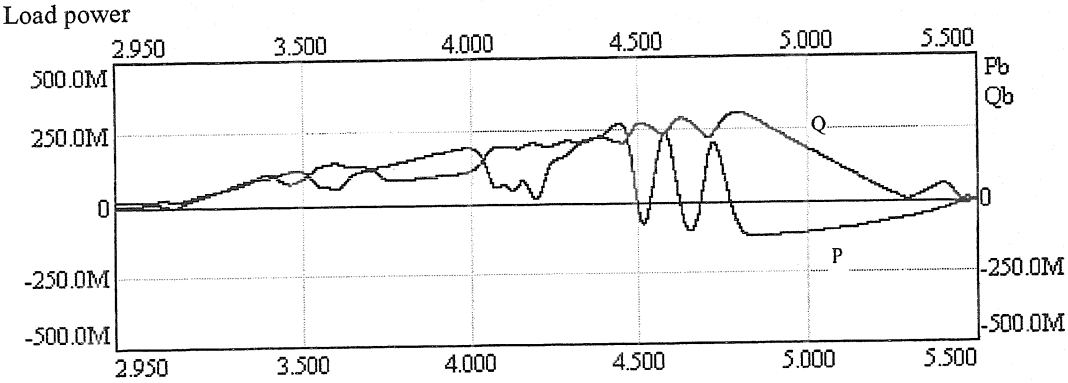
1. Simulation results for parallel connected generators with PI/PD controller -------- 1
2. Short circuit simulations -------- 5
3. Reactive power compensation -------- 22
4. Simulations applying filters of different time constants in the signal measurements -------- 26
5. Dynamic behaviour of the generators during parallel connection -------- 29
6. Parametrical studies performed for varying machine parmeters -------- 37
7. Dynamic response on step load and simulation of the current in the paralleling switch -------- 95

1. Simulation results for parallel connected generators with PI/PD controller

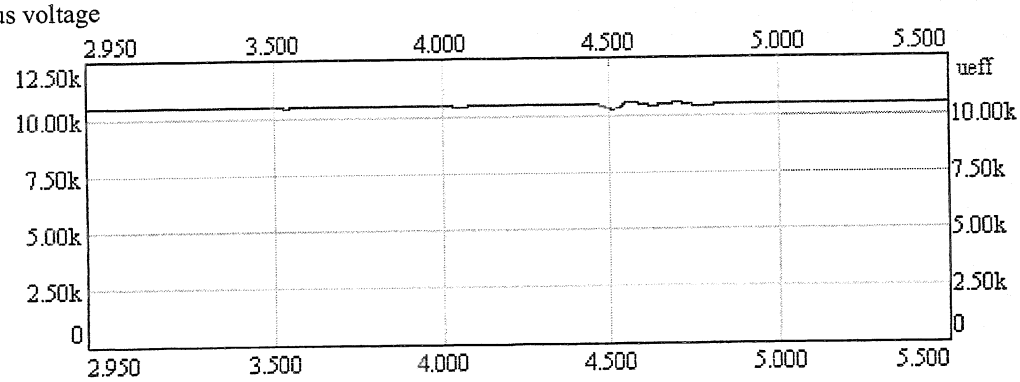
(1) Ideal parameter of the generators and no disturbance in the measurement



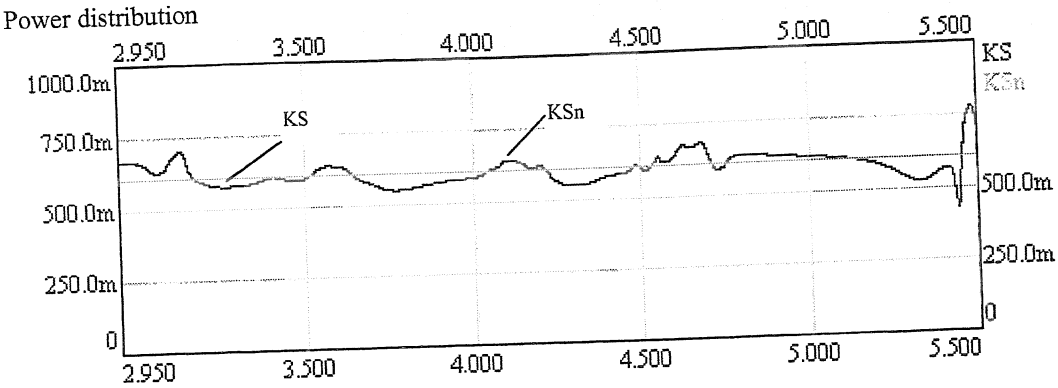
Load power



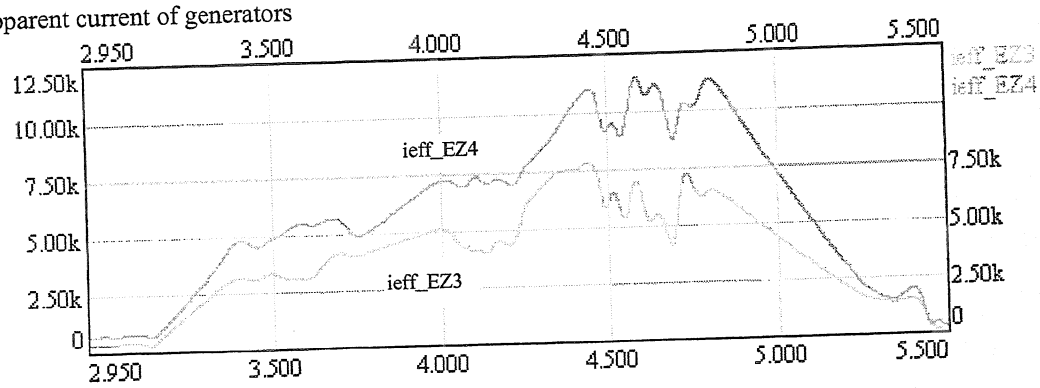
Bus voltage



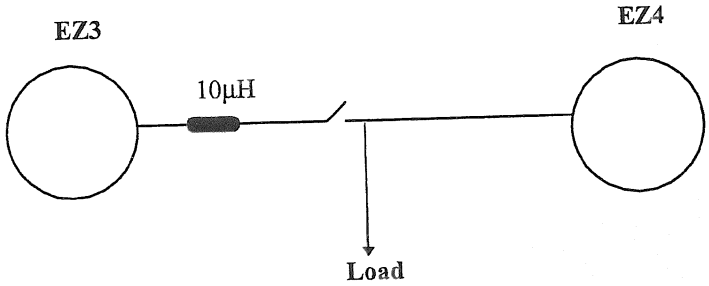
Power distribution



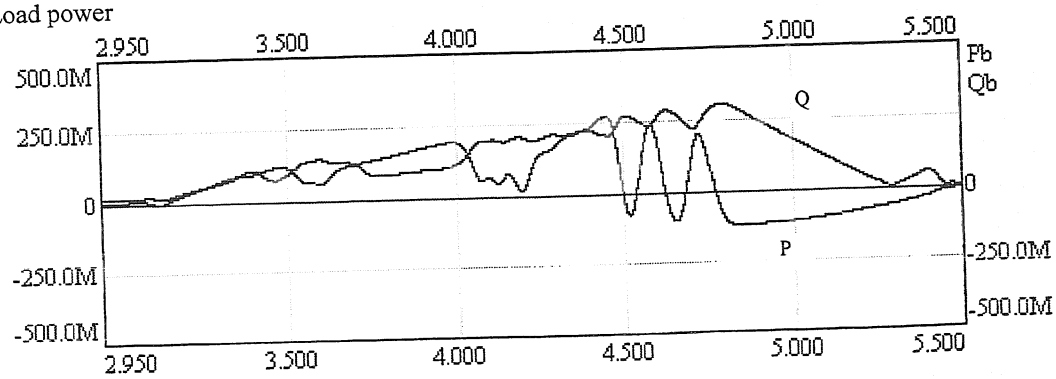
Apparent current of generators



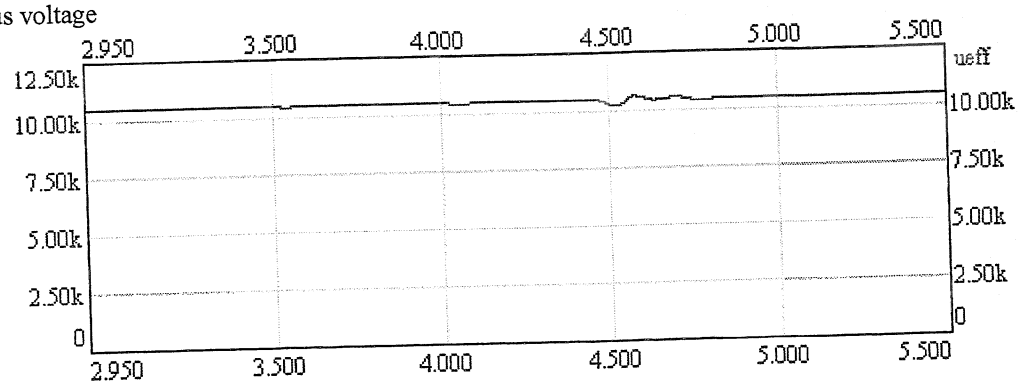
(2) Ideal parameter of the generators and 10μH inductance in series on EZ3 side



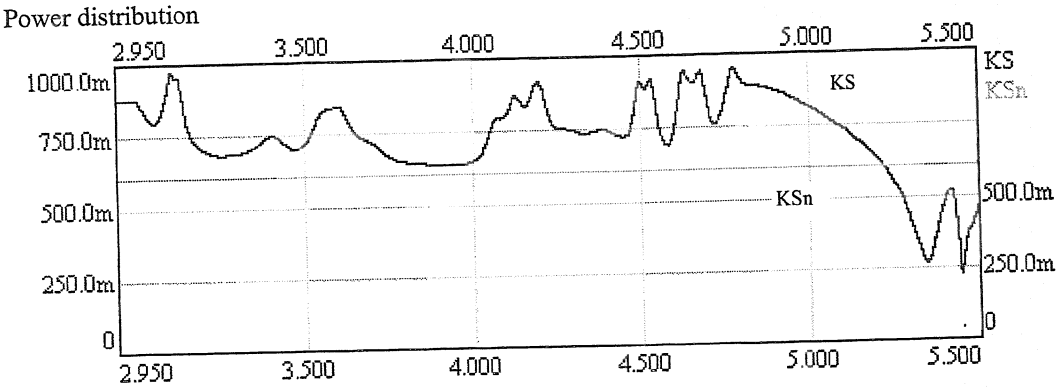
Load power



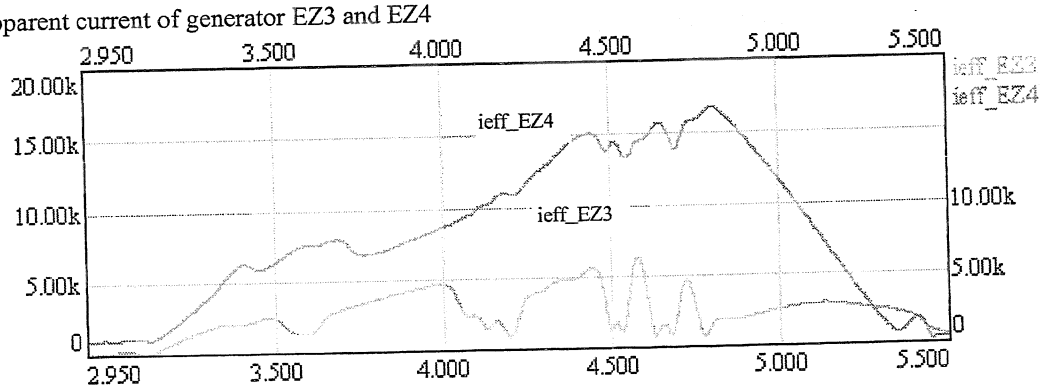
Bus voltage



Power distribution

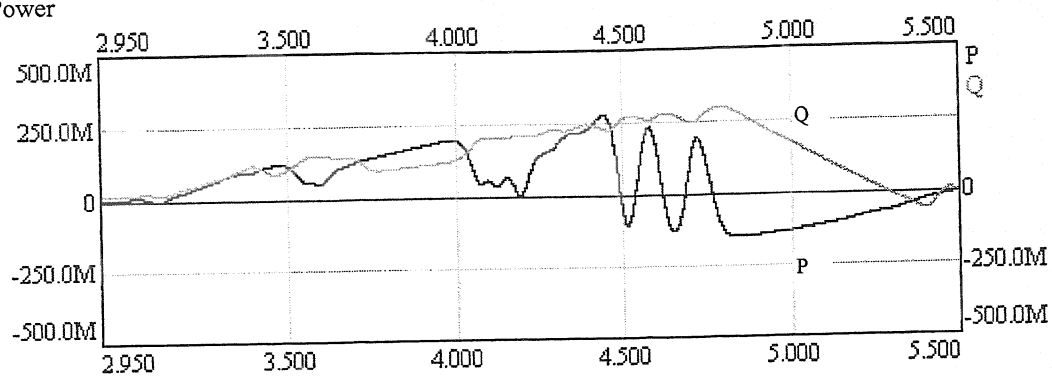


Apparent current of generator EZ3 and EZ4

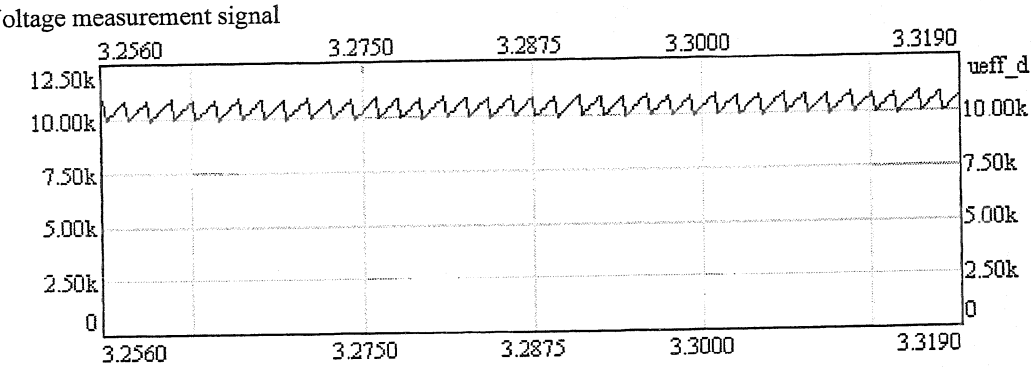


3. 3.5% disturbance signal in measurement

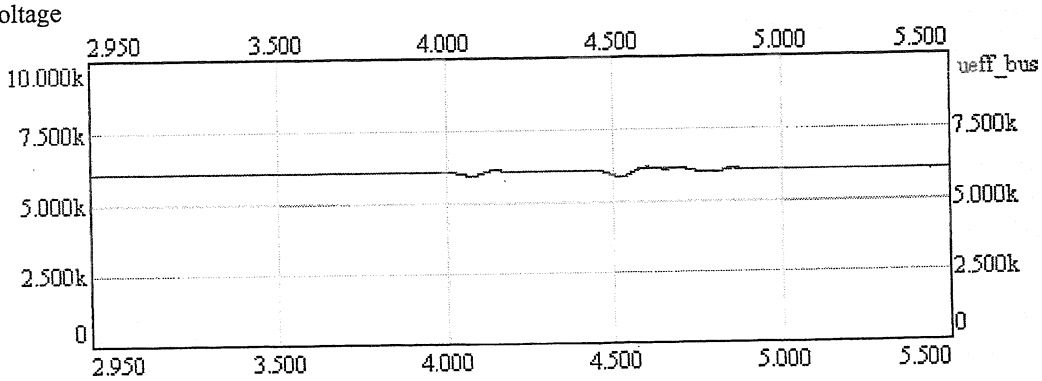
Power



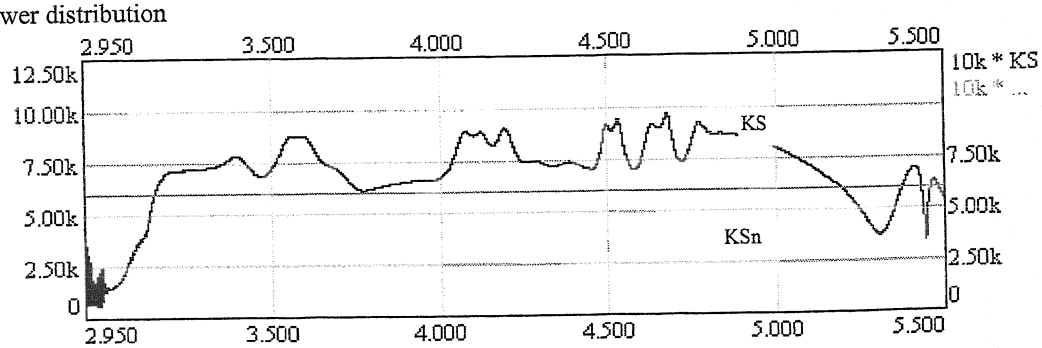
Voltage measurement signal



Voltage



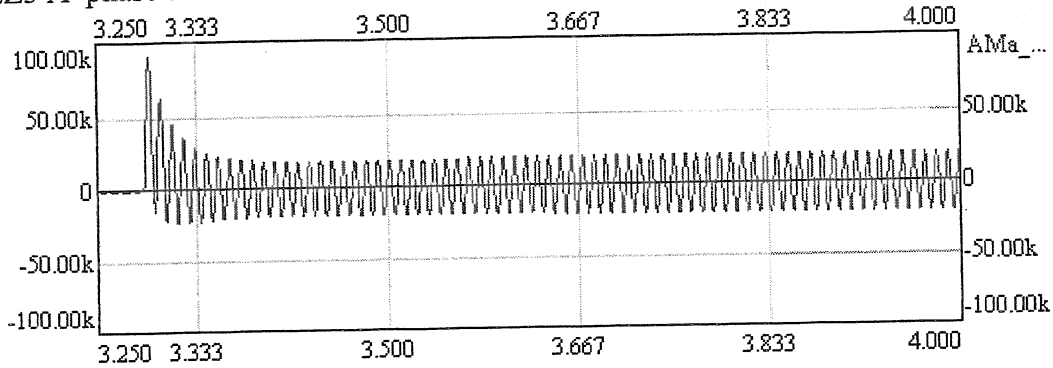
Power distribution



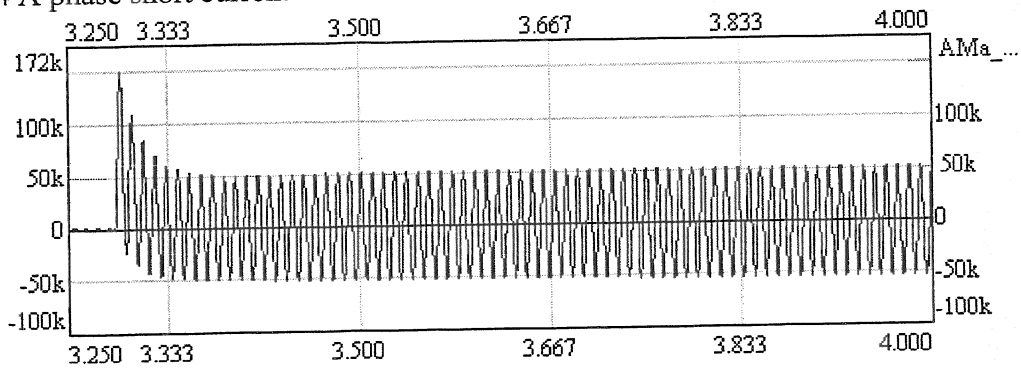
2. Short circuit simulations

(1) Short circuit (normal generator parameters and no inverse excitation)

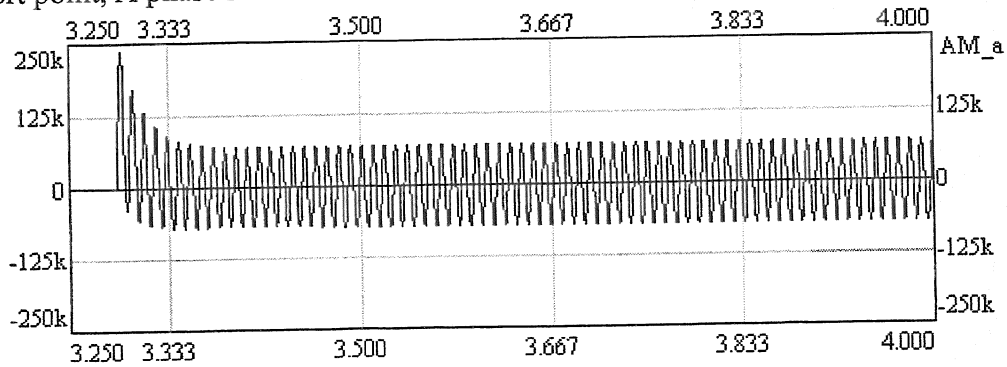
EZ3 A phase short current



EZ4 A phase short current



Short point, A phase short current

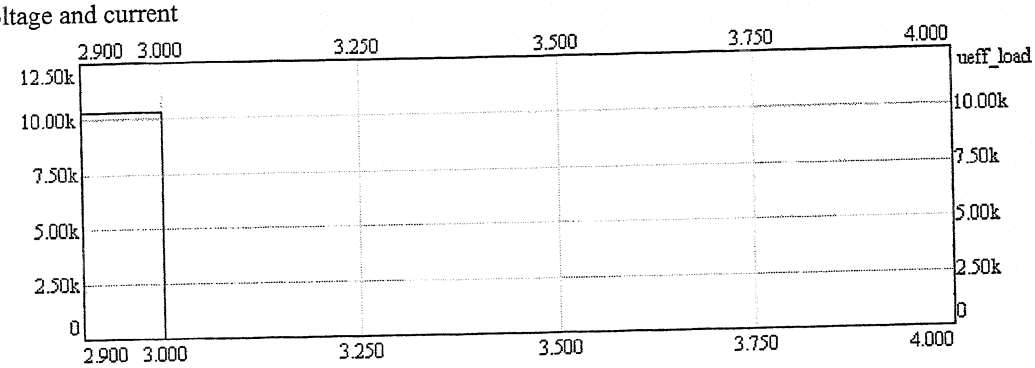


(2) Short circuit with worst parameters of generators

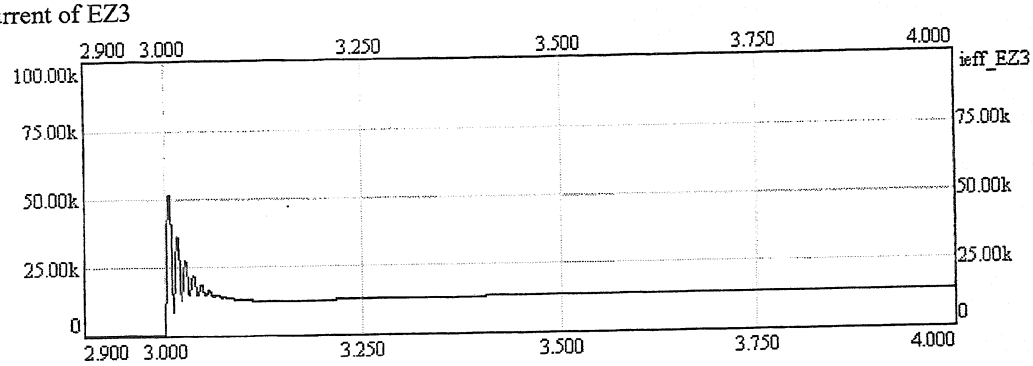
(EZ3 and EZ4 Rkq*2, Rs*2, Ls*1.4)

a. Three phase short

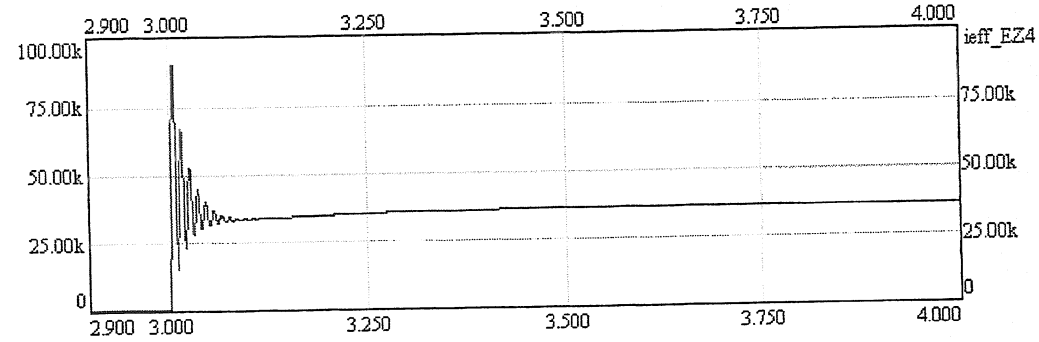
Voltage and current



Current of EZ3

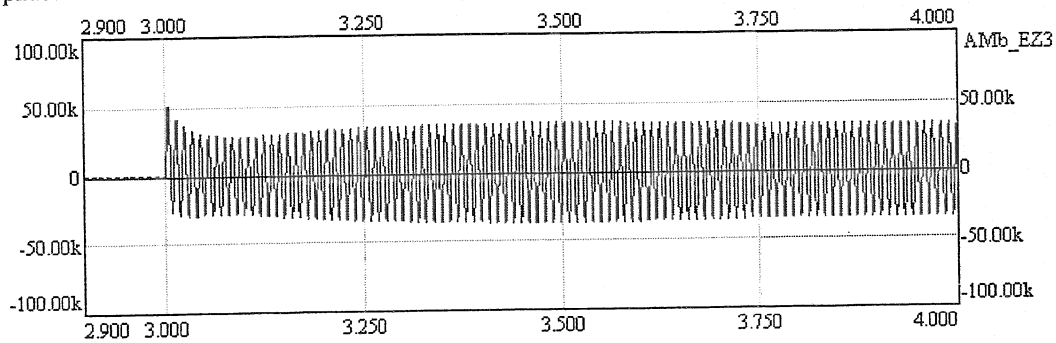


Current of EZ4

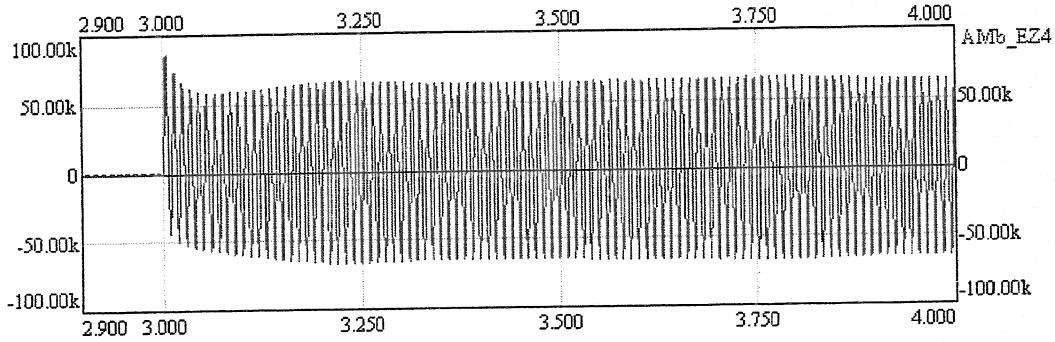


b. B phase short

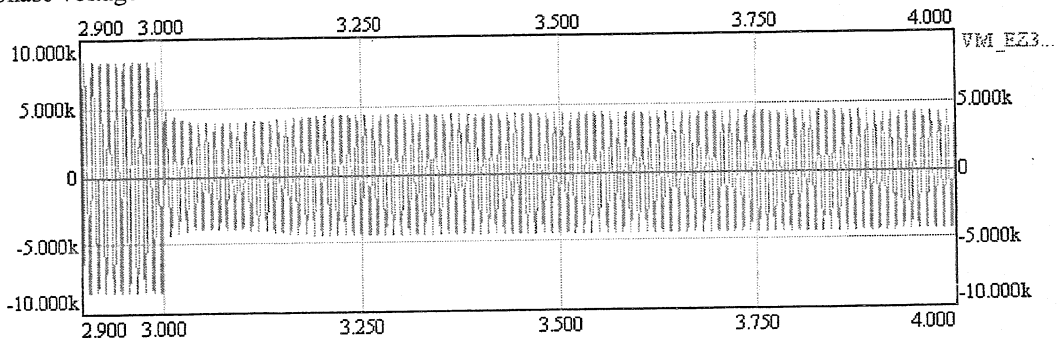
B phase current of EZ3



B phase current of EZ4

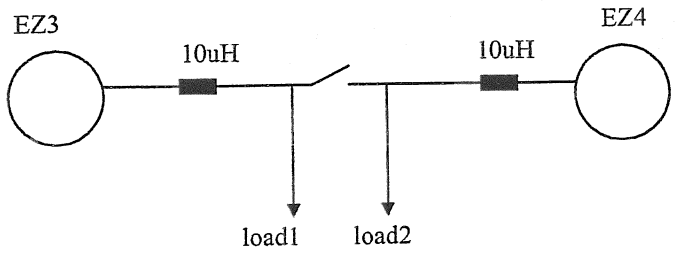


B phase voltage of EZ3



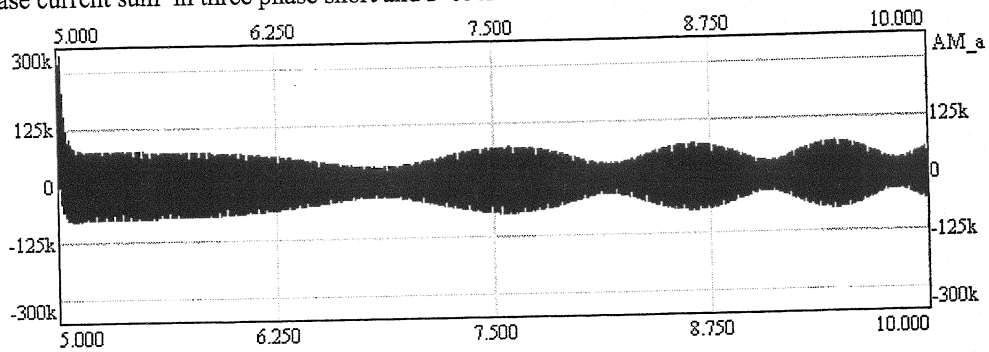
(3) . Short circuit simulation at different frequencies

(a) Short circuit current calculation near load side, f=85HZ

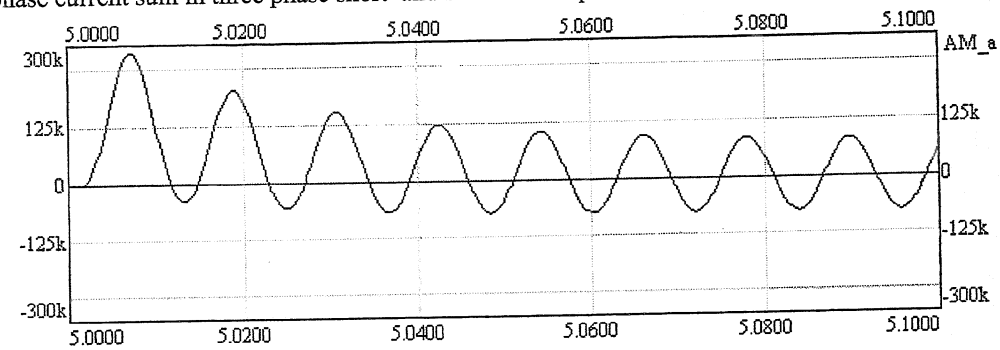


(a1) three phase short

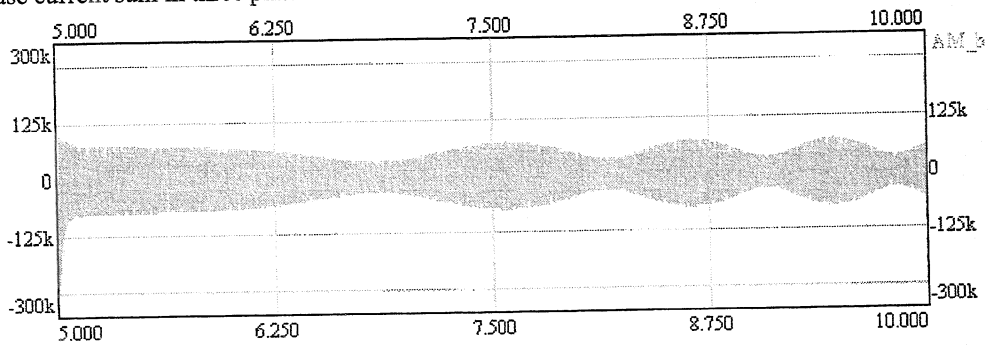
A phase current sum in three phase short and f=85HZ



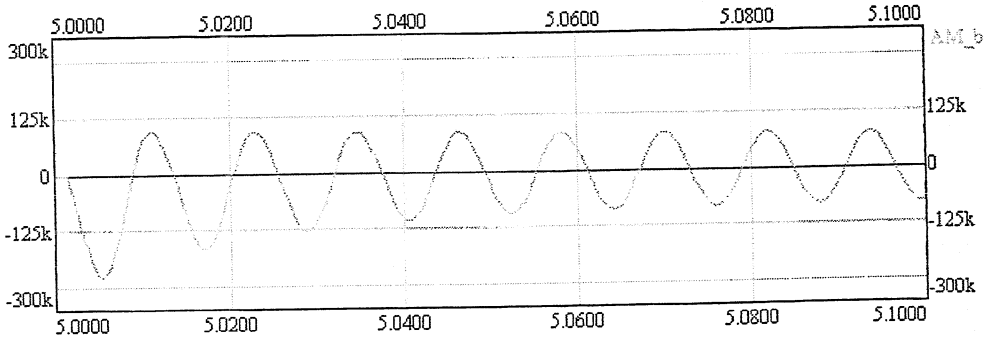
A phase current sum in three phase short and f=85HZ---expand



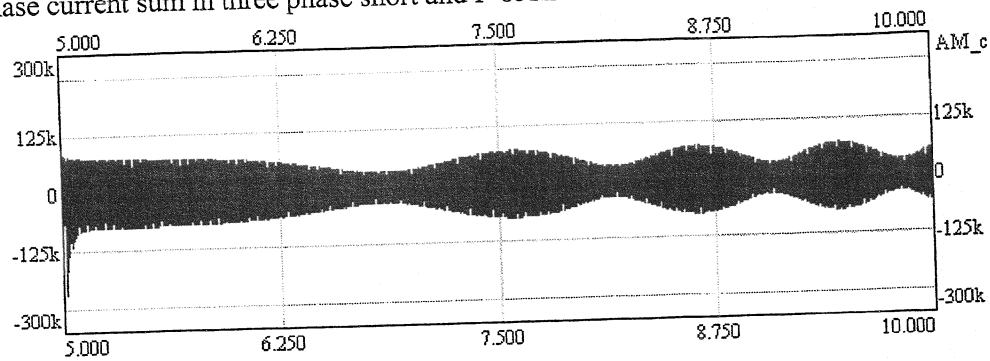
B phase current sum in three phase short f=85HZ



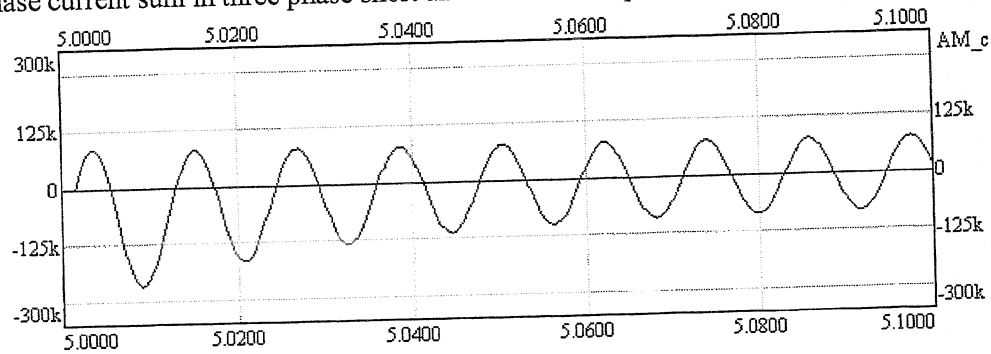
B phase current sum in three phase short and f=85HZ---expand



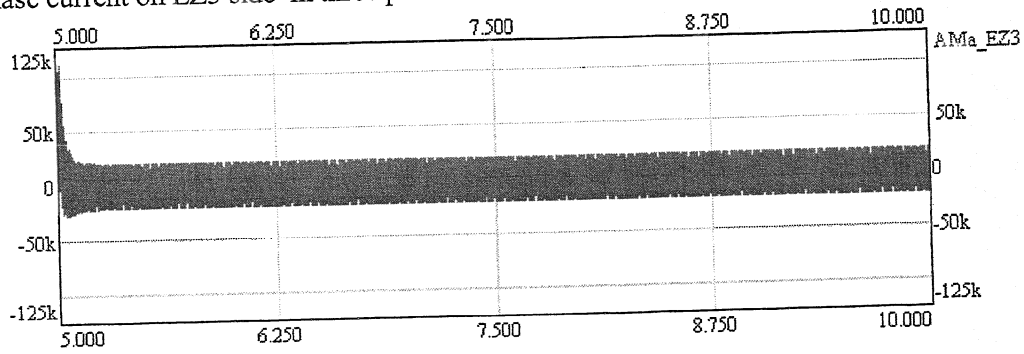
C phase current sum in three phase short and f=85HZ



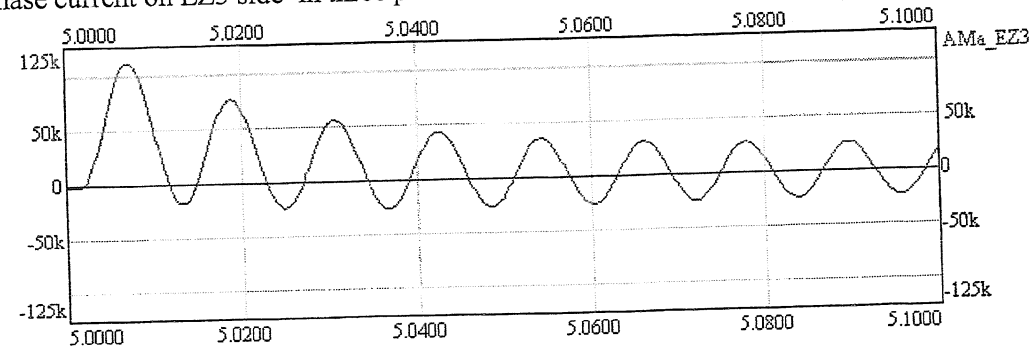
C phase current sum in three phase short and f=85HZ---expand



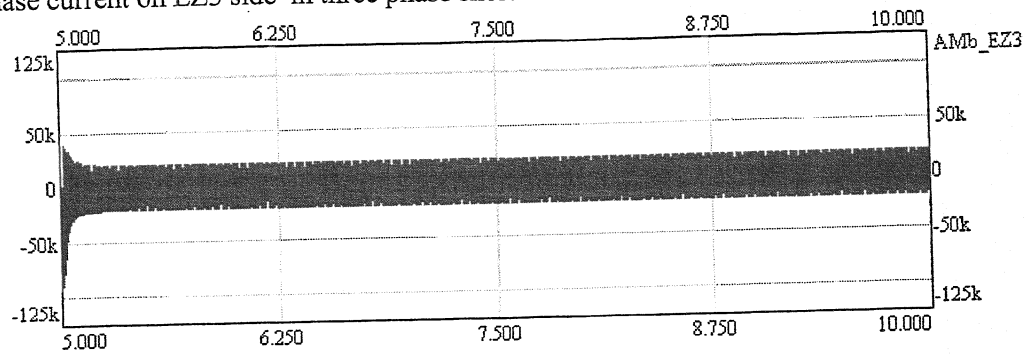
A phase current on EZ3 side in three phase short and f=85HZ



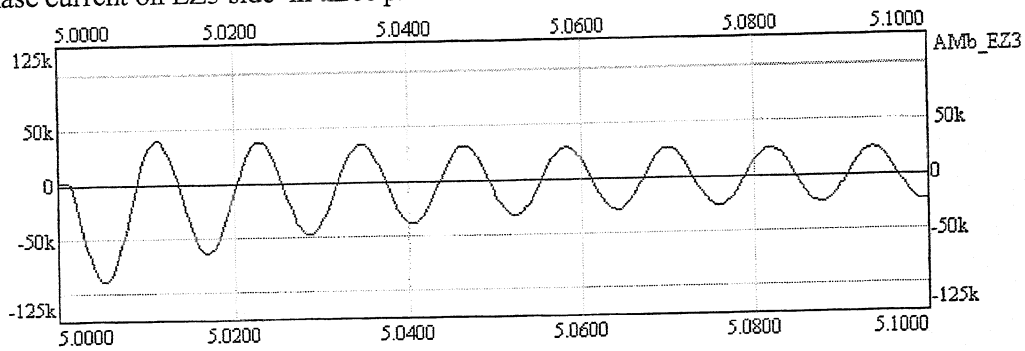
A phase current on EZ3 side in three phase short and f=85HZ---expand



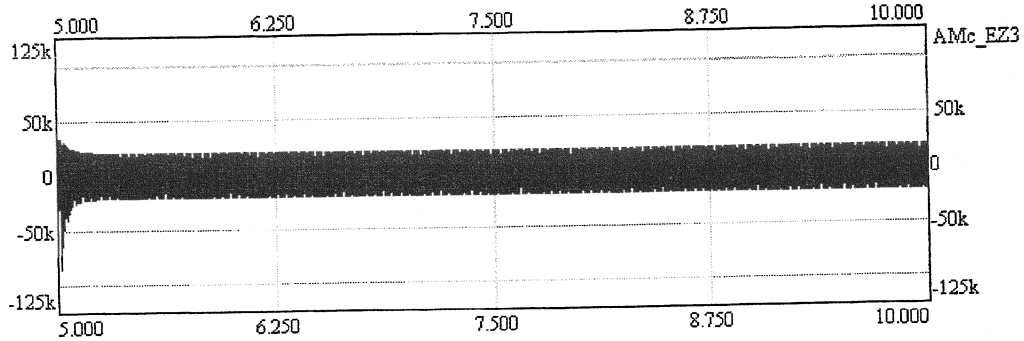
B phase current on EZ3 side in three phase short and f=85HZ



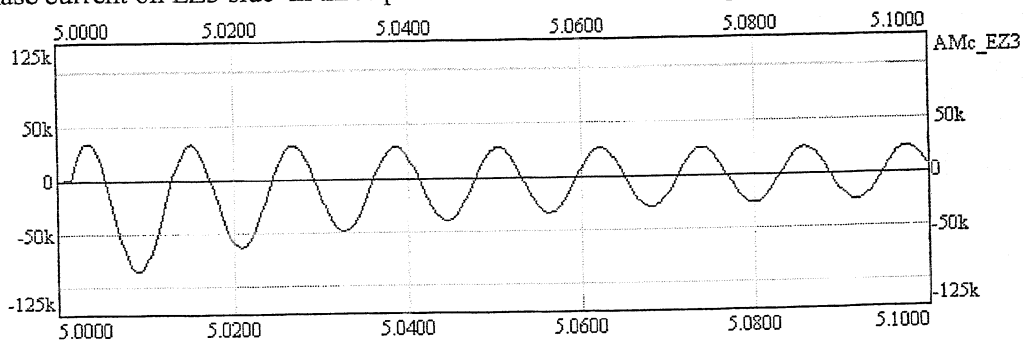
B phase current on EZ3 side in three phase short and f=85HZ---expand



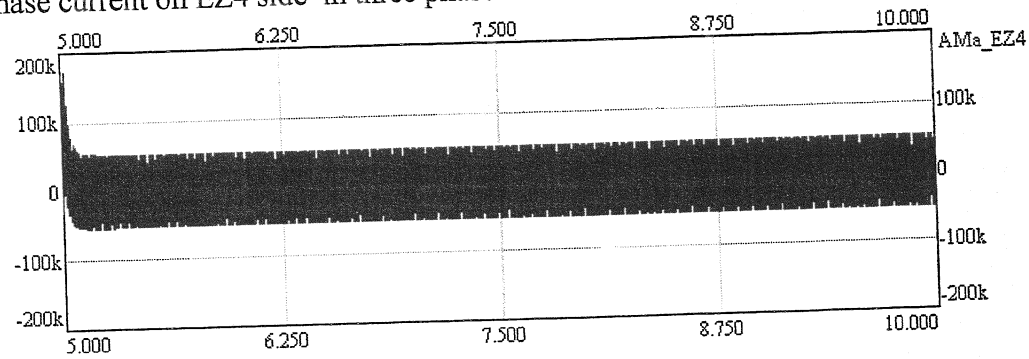
C phase current on EZ3 side in three phase short and f=85HZ



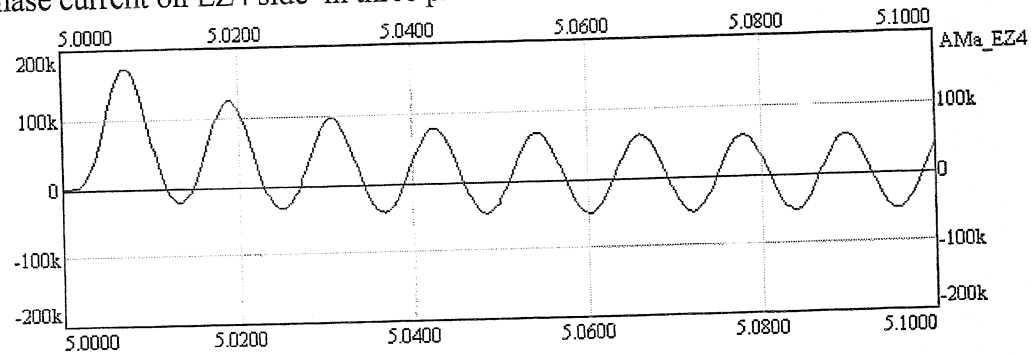
C phase current on EZ3 side in three phase short and f=85HZ---expand



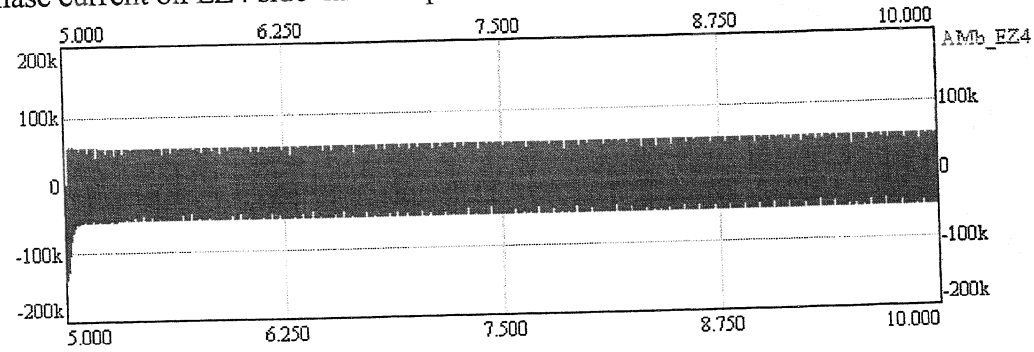
A phase current on EZ4 side in three phase short and f=85HZ



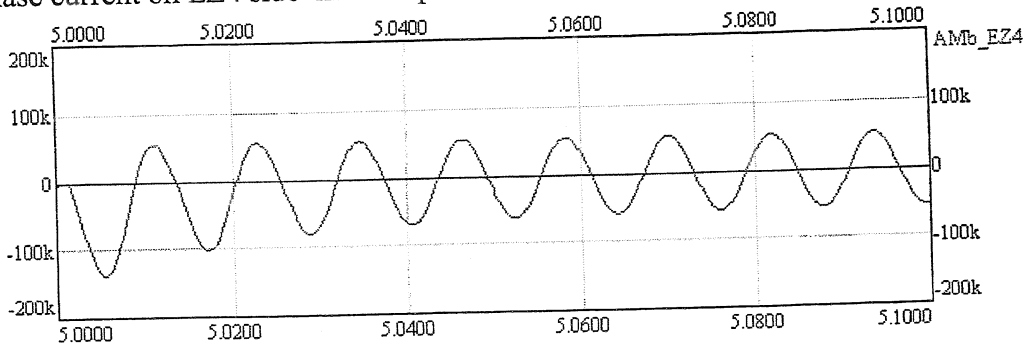
A phase current on EZ4 side in three phase short and f=85HZ---expand



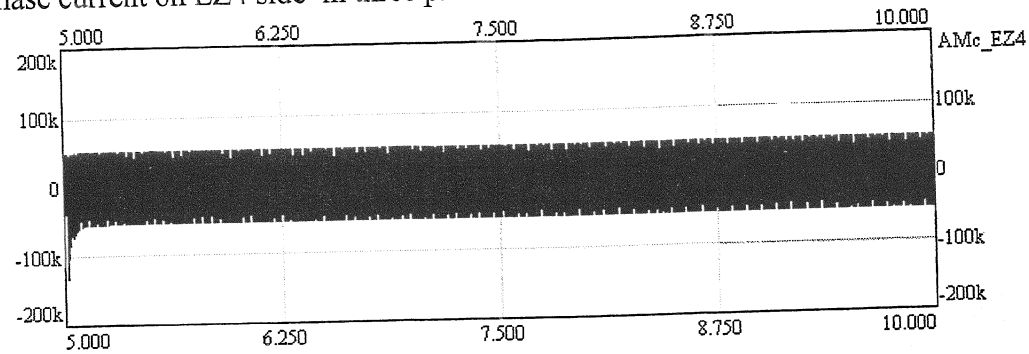
B phase current on EZ4 side in three phase short and f=85HZ



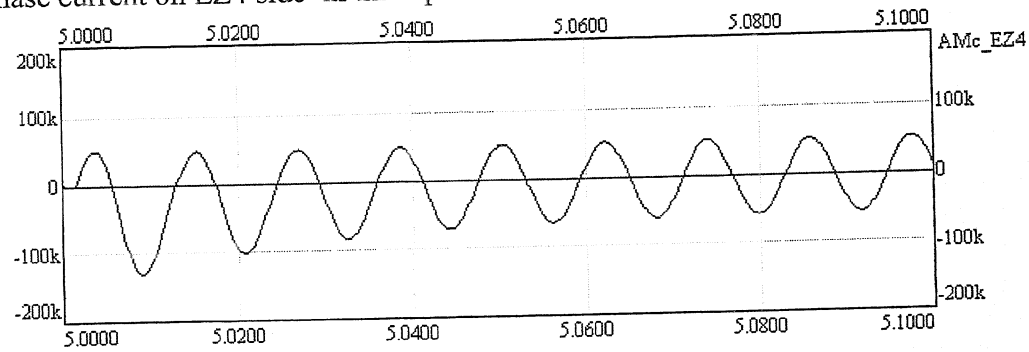
B phase current on EZ4 side in three phase short and f=85HZ---expand



C phase current on EZ4 side in three phase short and f=85HZ

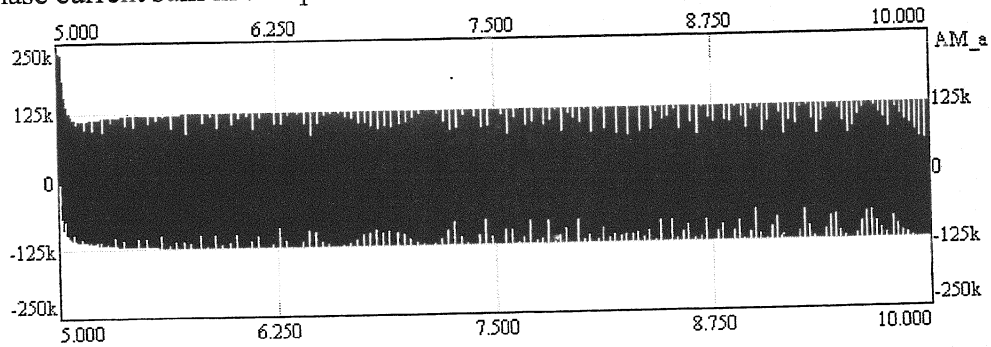


C phase current on EZ4 side in three phase short and f=85HZ---expand

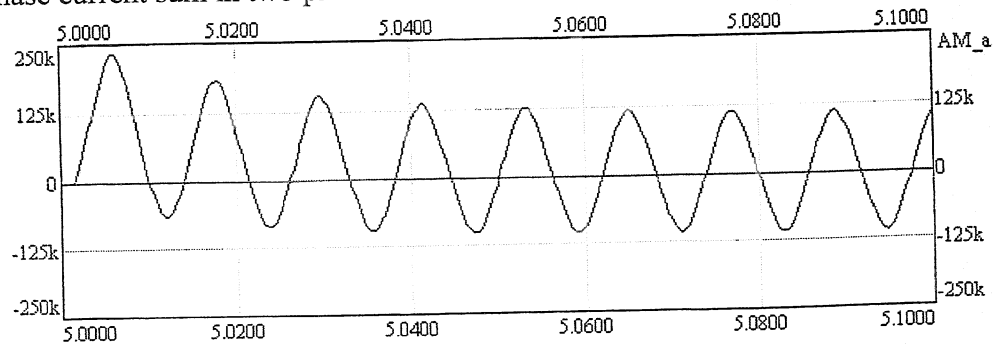


(a2) Two phase short circuit in f=85HZ (A and B phase)

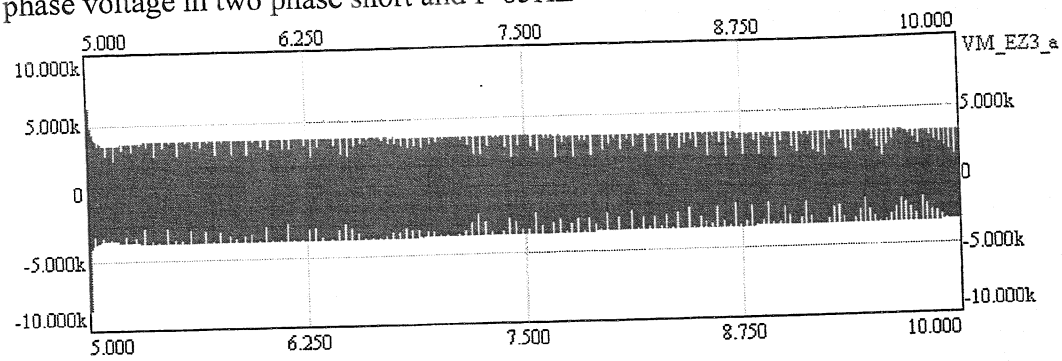
A phase current sum in two phase short and f=85HZ



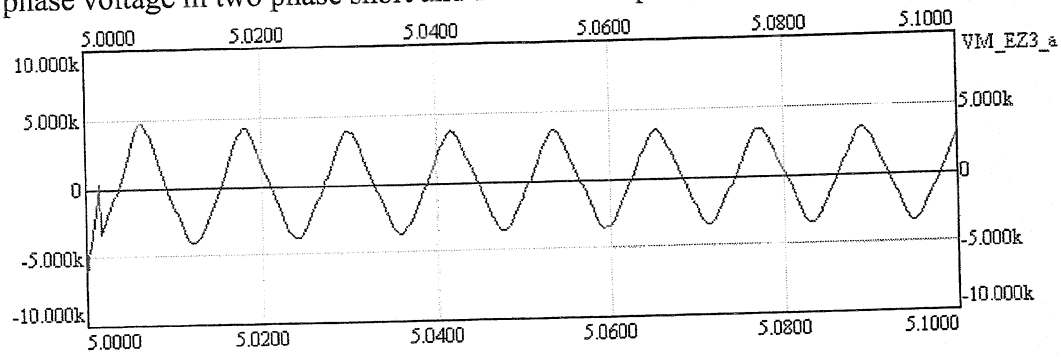
A phase current sum in two phase short and f=85HZ---expand



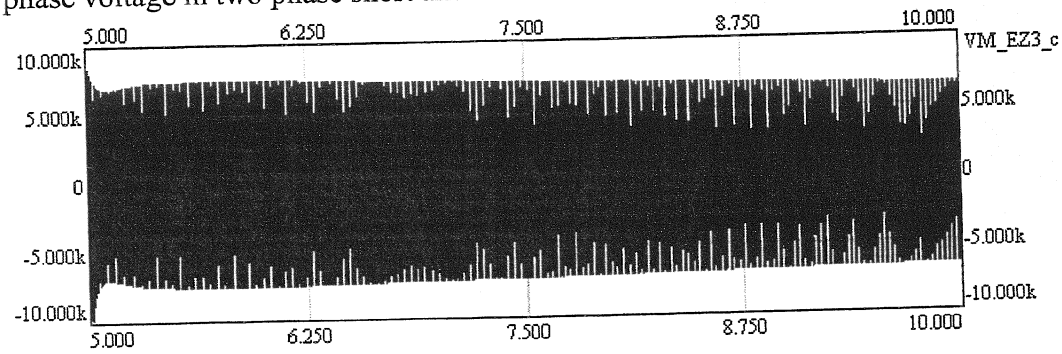
A phase voltage in two phase short and f=85HZ



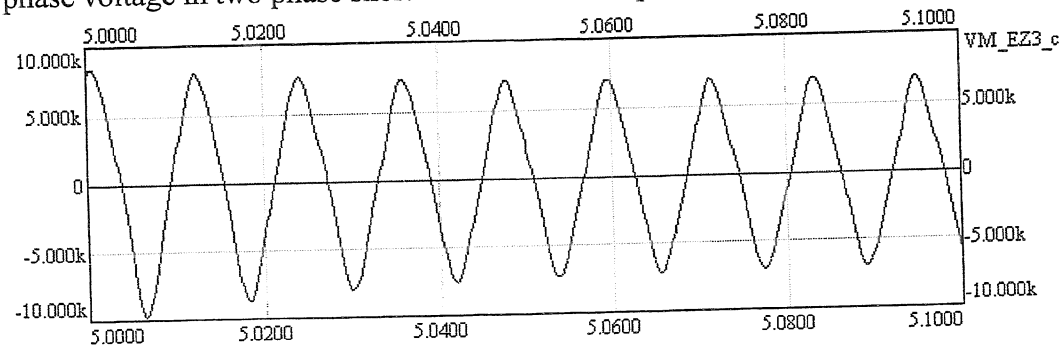
A phase voltage in two phase short and f=85HZ---expand



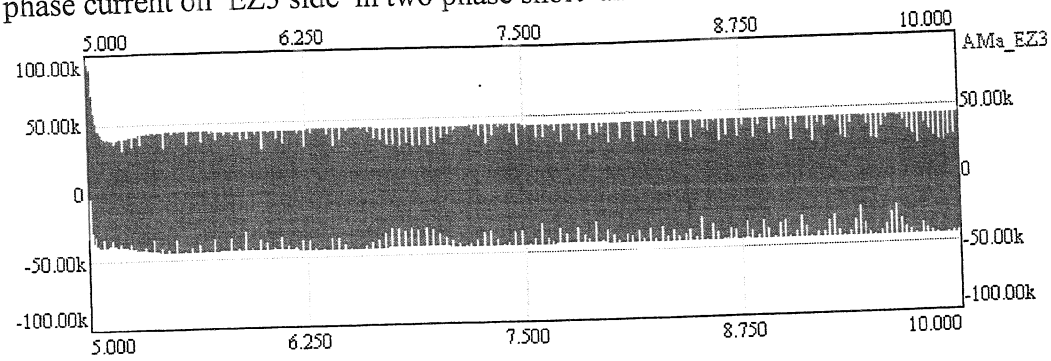
C phase voltage in two phase short and f=85HZ



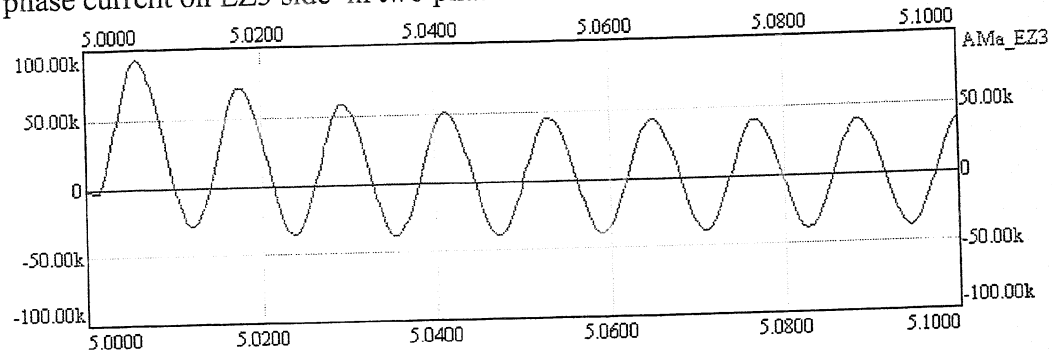
C phase voltage in two phase short and f=85HZ---expand



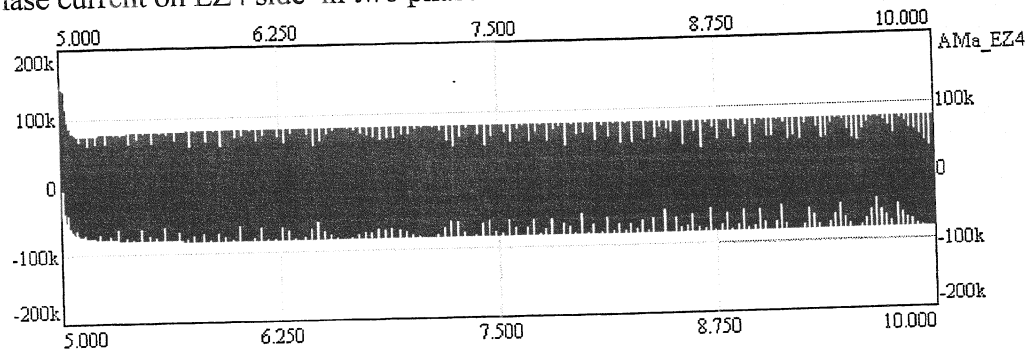
A phase current on EZ3 side in two phase short and f=85HZ



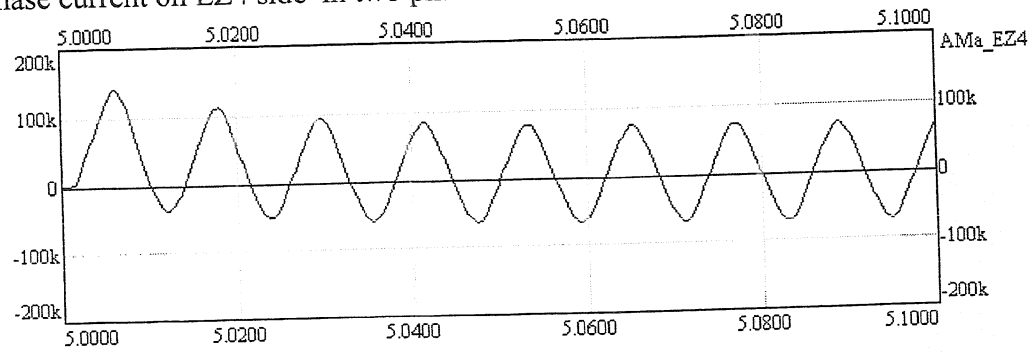
A phase current on EZ3 side in two phase short and f=85HZ---expand



A phase current on EZ4 side in two phase short and f=85HZ



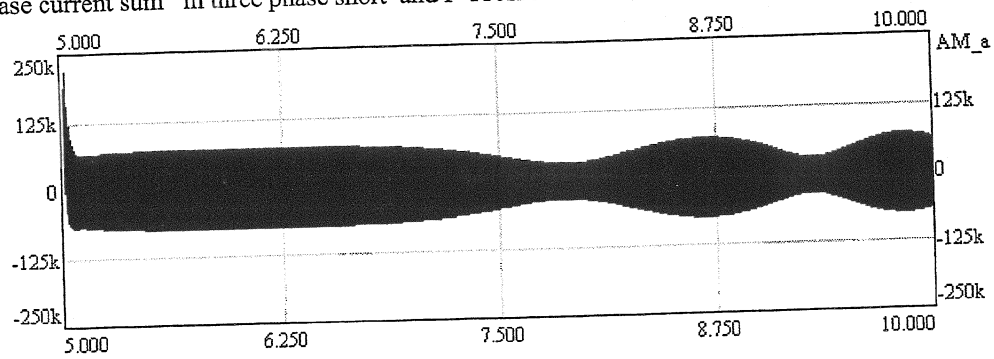
A phase current on EZ4 side in two phase short and f=85HZ---expand



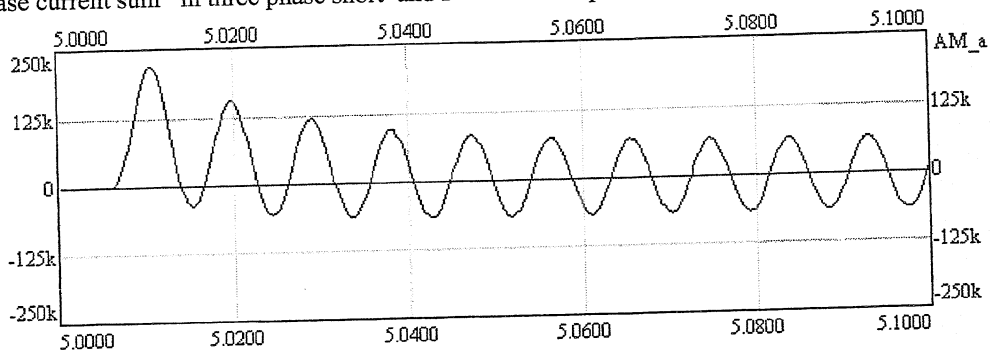
(b) Short circuit current calculation near load side, f=110HZ

(b1) three phase short

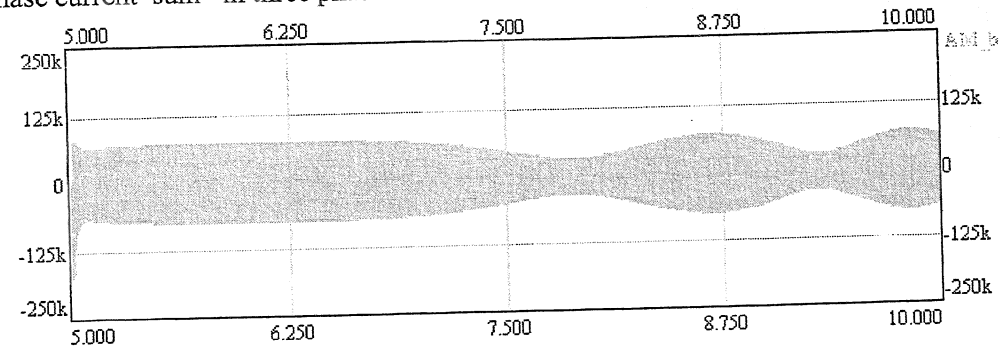
A phase current sum in three phase short and f=110HZ



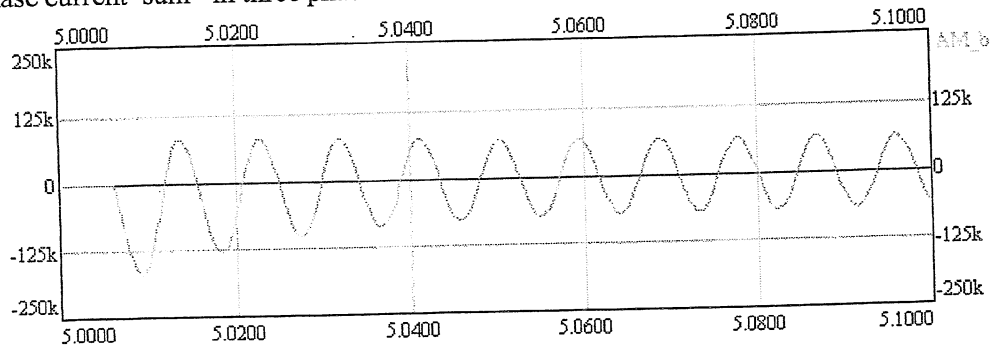
A phase current sum in three phase short and f=110HZ---expand



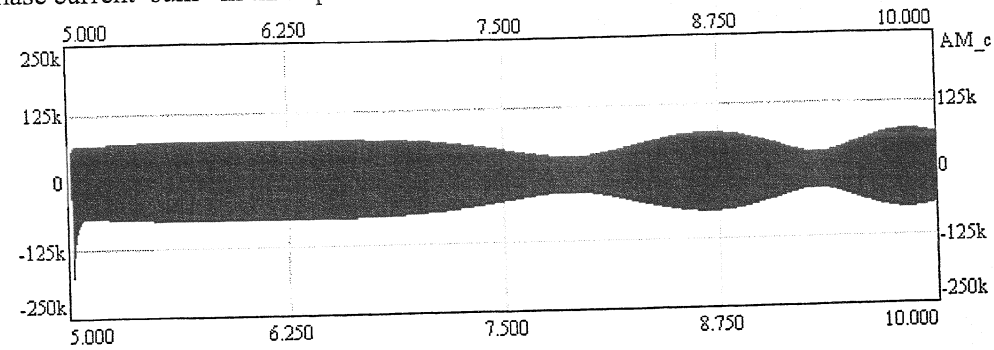
B phase current sum in three phase short and f=110HZ



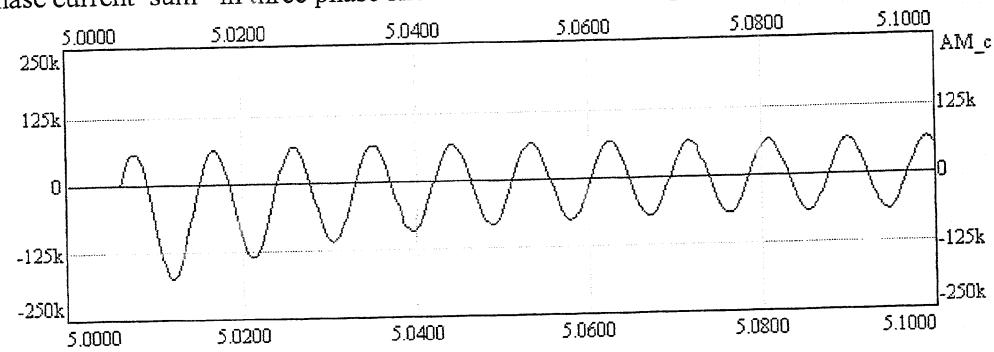
B phase current sum in three phase short and f=110HZ---expand



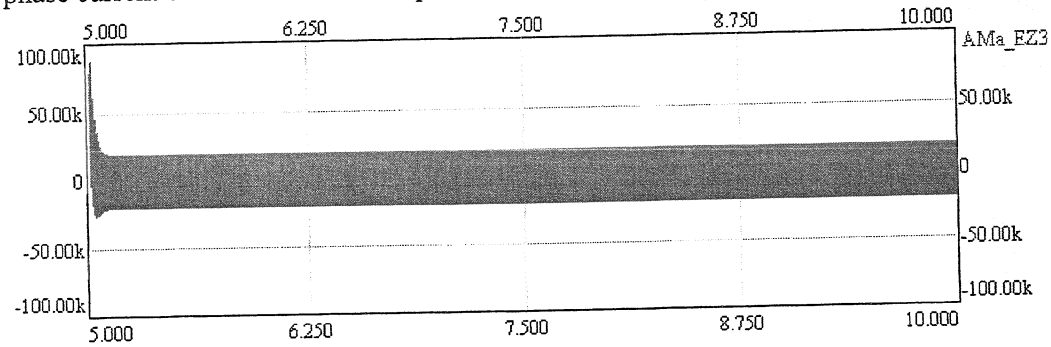
C phase current sum in three phase short and f=110HZ



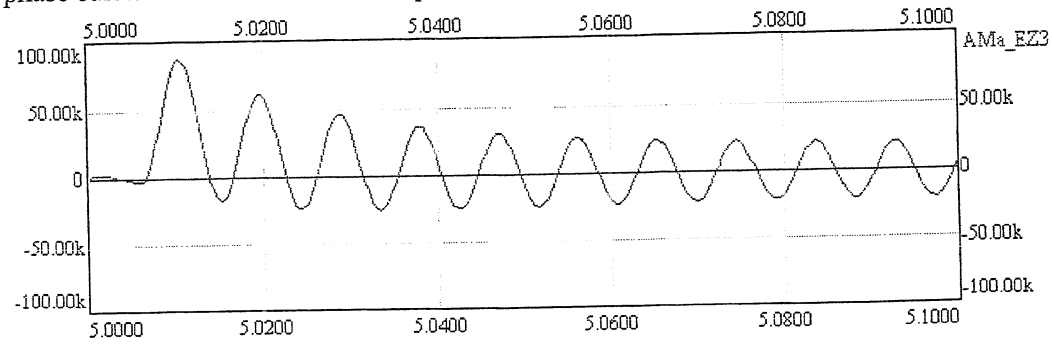
C phase current sum in three phase short and f=110HZ---expand



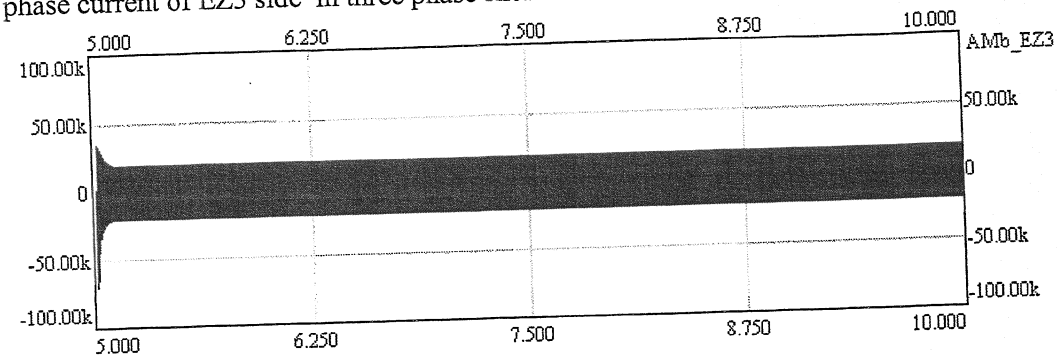
A phase current on EZ3 side in three phase short and f=110HZ



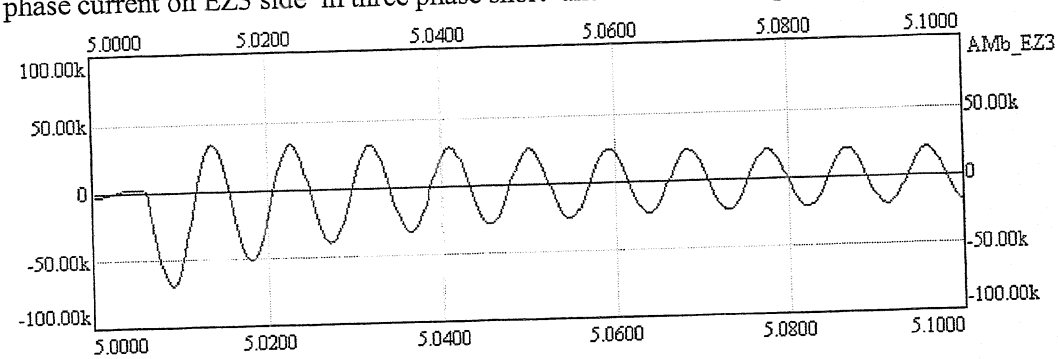
A phase current on EZ3 side in three phase short and f=110HZ---expand



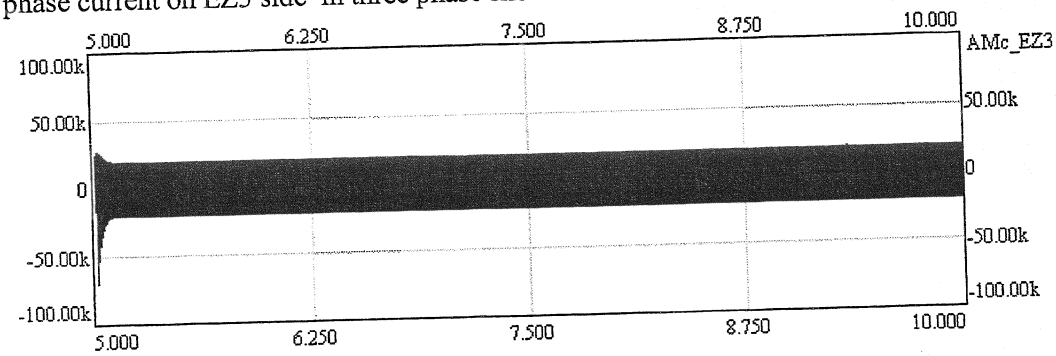
B phase current of EZ3 side in three phase short and f=110HZ



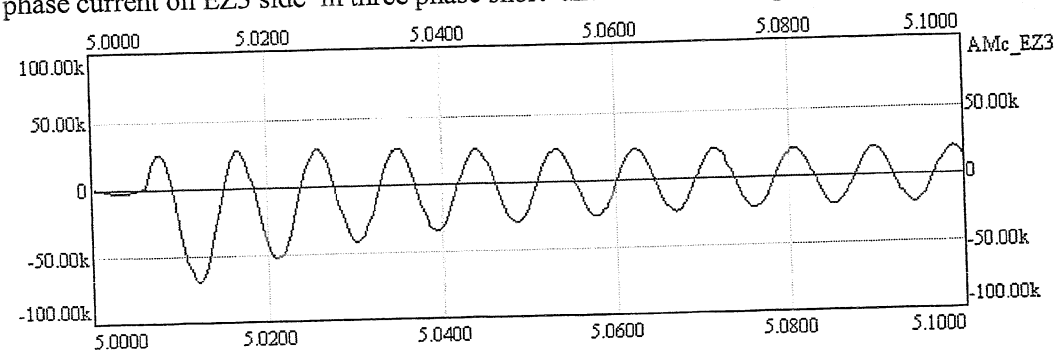
B phase current on EZ3 side in three phase short and f=110HZ---expand



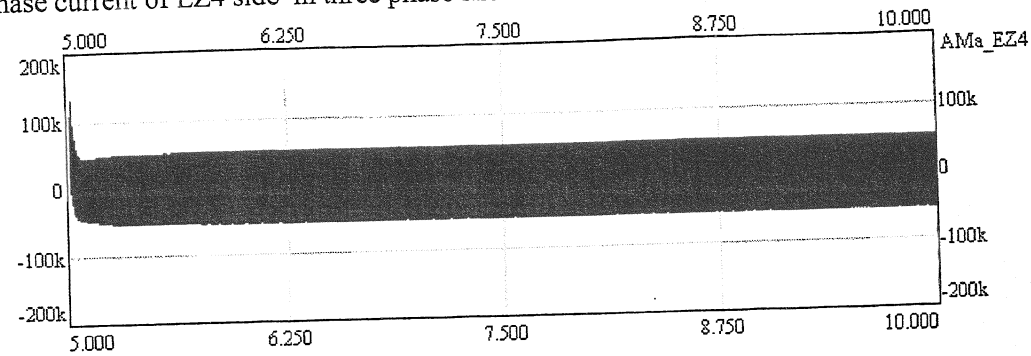
C phase current on EZ3 side in three phase short and f=110HZ



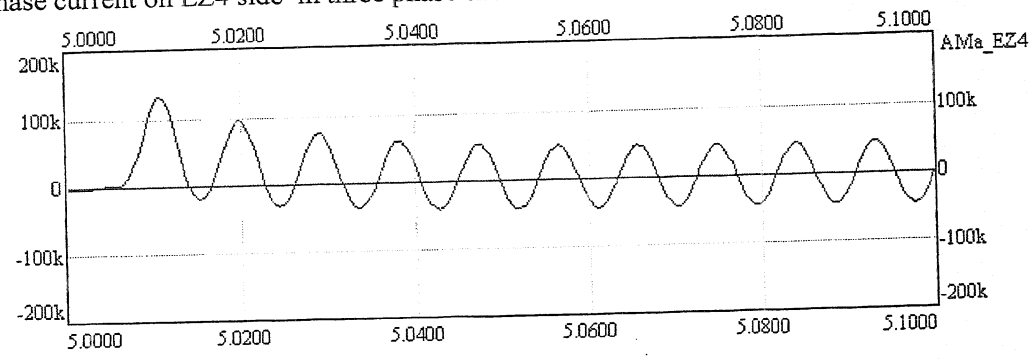
C phase current on EZ3 side in three phase short and f=110HZ---expand



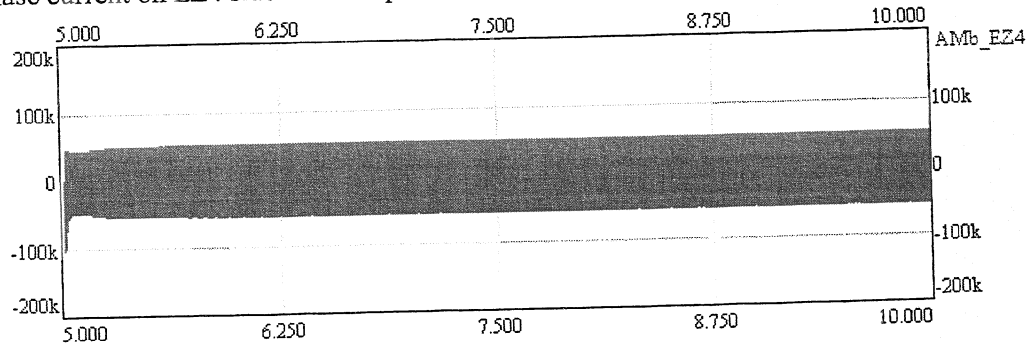
A phase current of EZ4 side in three phase short and f=110HZ



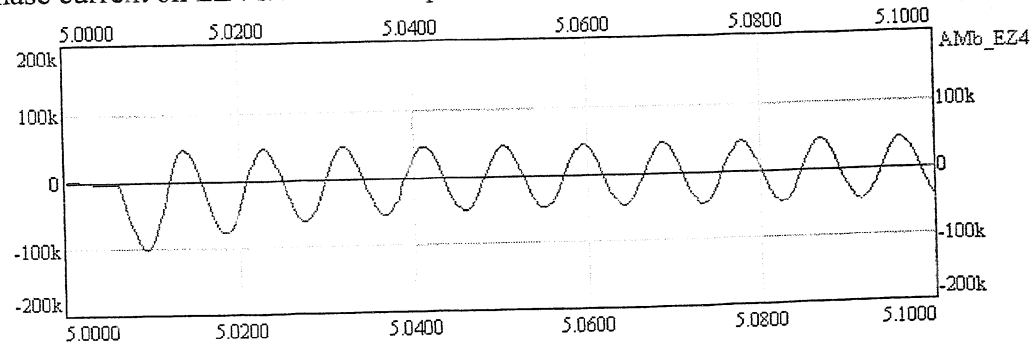
A phase current on EZ4 side in three phase short and f=110HZ---expand



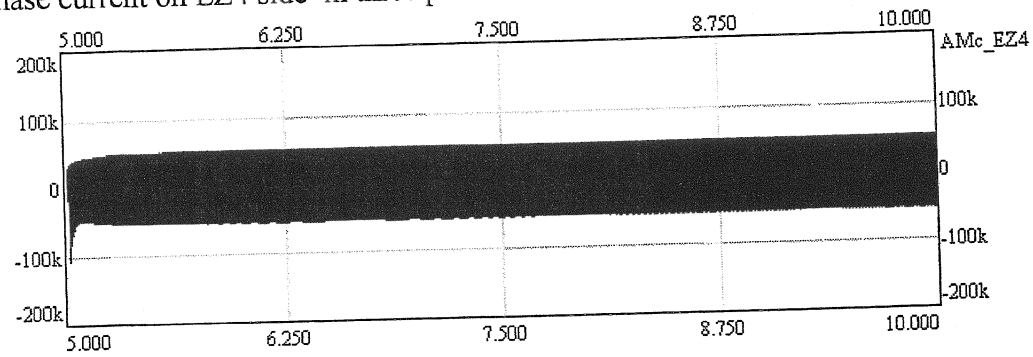
B phase current on EZ4 side in three phase short and f=110HZ



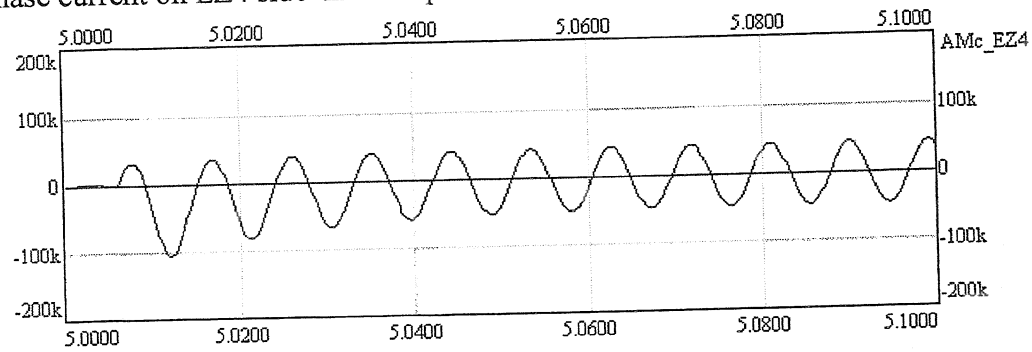
B phase current on EZ4 side in three phase short and f=110HZ---expand



C phase current on EZ4 side in three phase short and f=110HZ

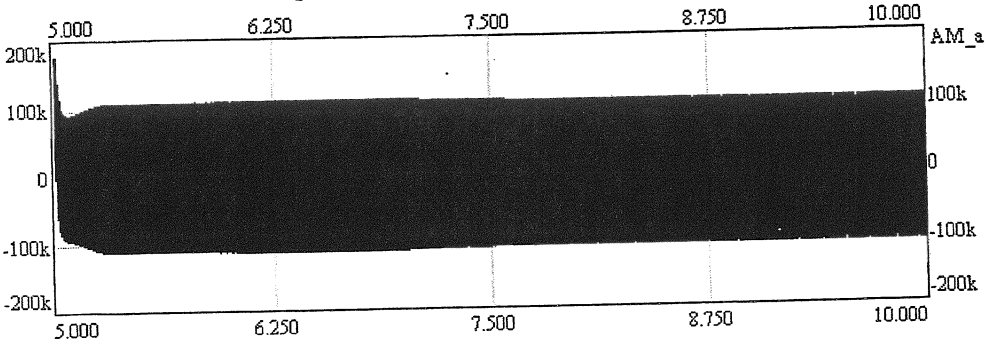


C phase current on EZ4 side in three phase short and f=110HZ---expand

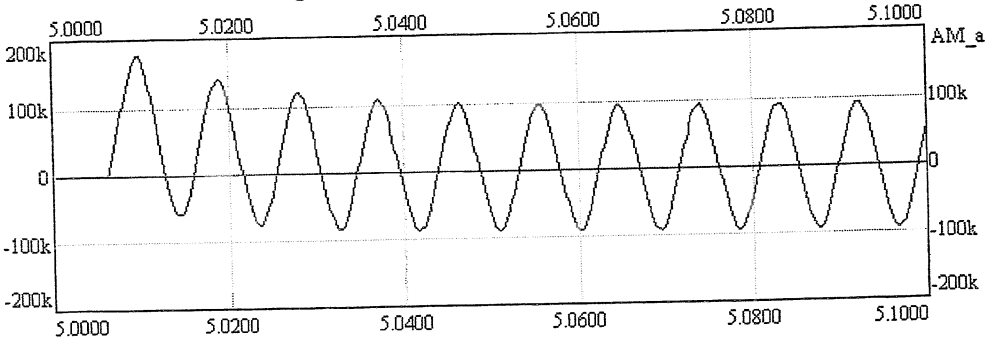


(b2) Two phase short at f=110HZ (A and B phase)

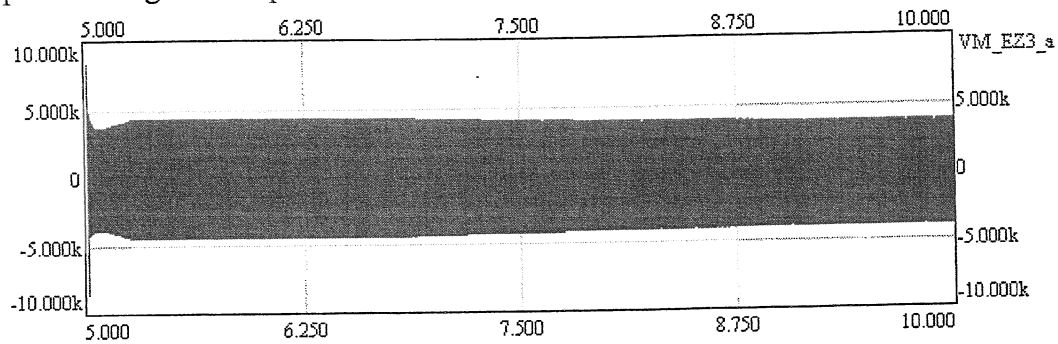
A phase current sum in two phase short and f=110HZ



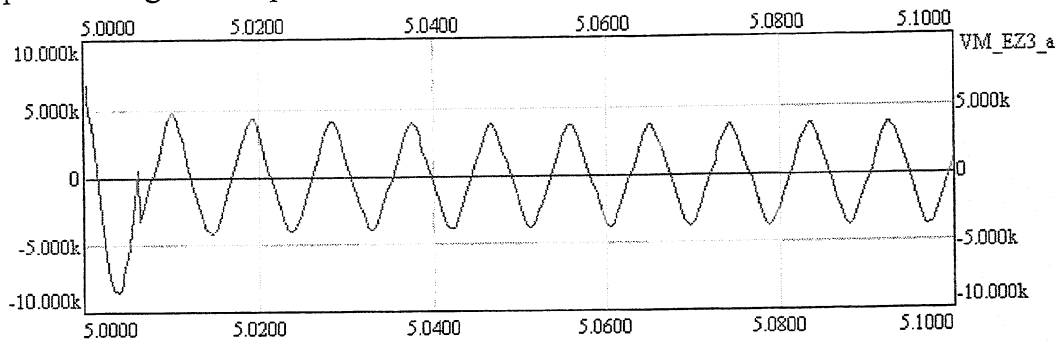
A phase current sum in two phase short and f=110HZ---expand



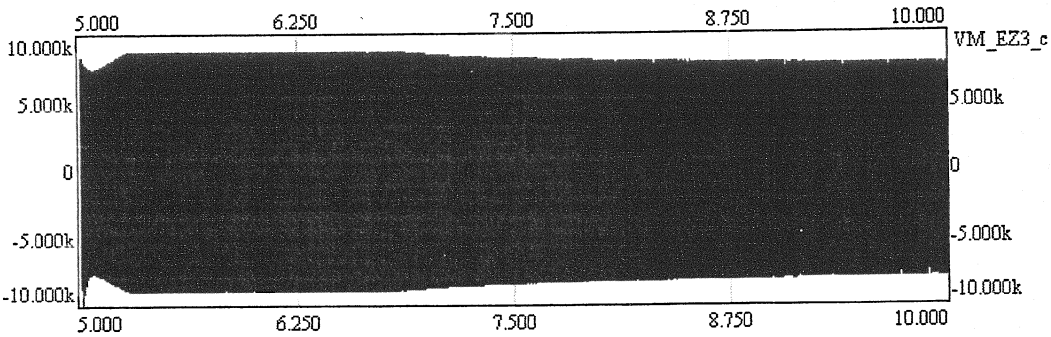
A phase voltage in two phase short and f=110HZ



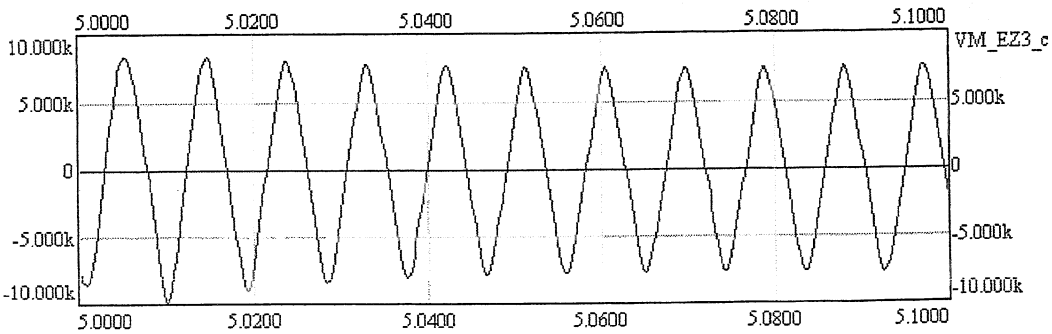
A phase voltage in two phase short and f=110HZ---expand



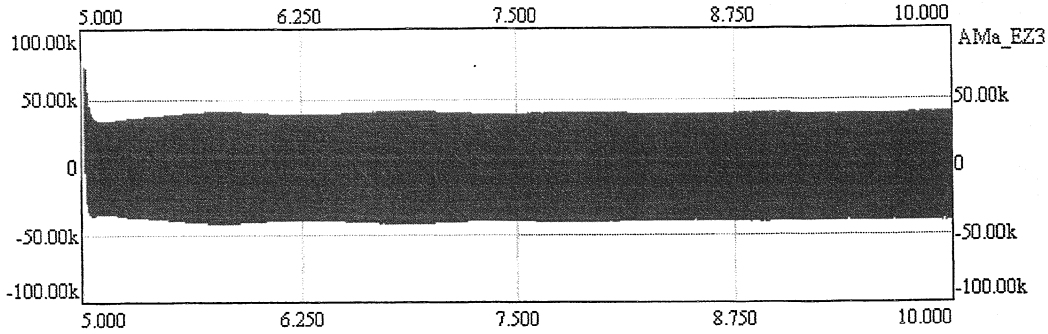
C phase voltage in two phase short and f=110HZ



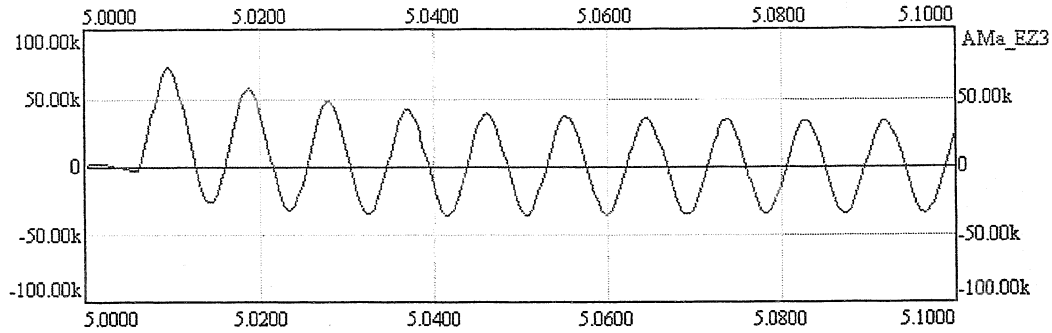
C phase voltage in two phase short and f=110HZ---expand



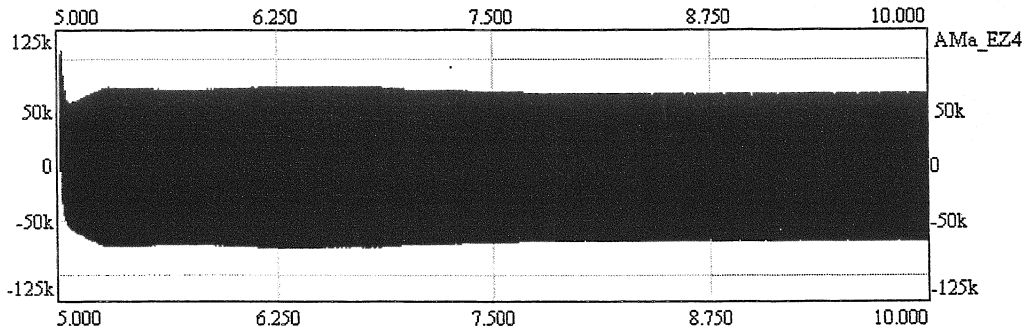
A phase current on EZ3 side in two phase short and f=110HZ



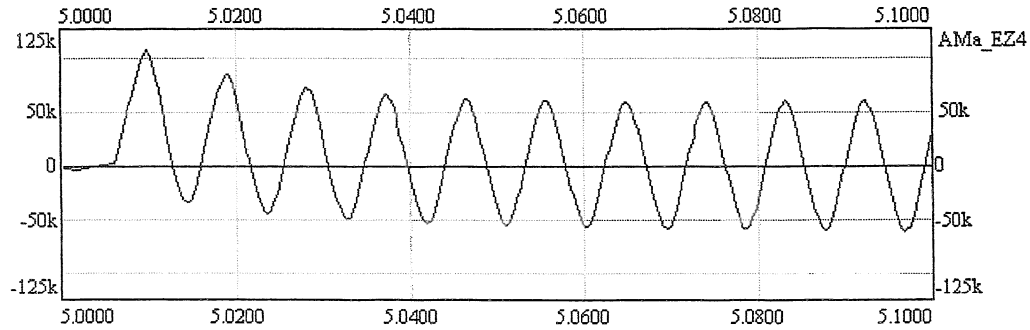
A phase current on EZ3 side in two phase short and f=110HZ---expand



A phase current on EZ4 side in two phase short and f=110HZ

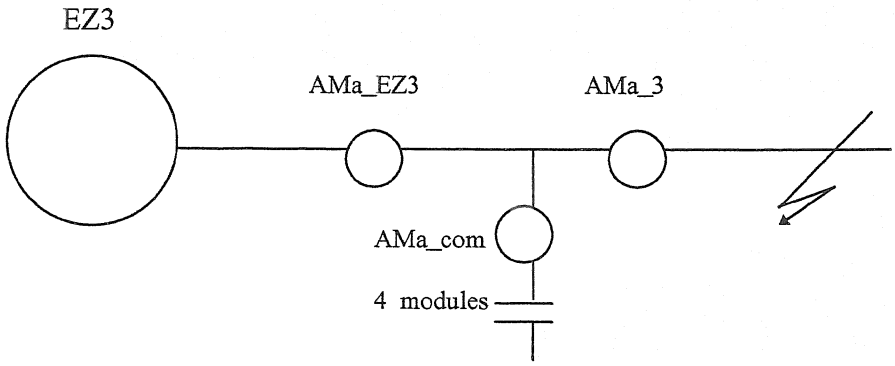


A phase current on EZ4 side in two phase short and f=110HZ---expand



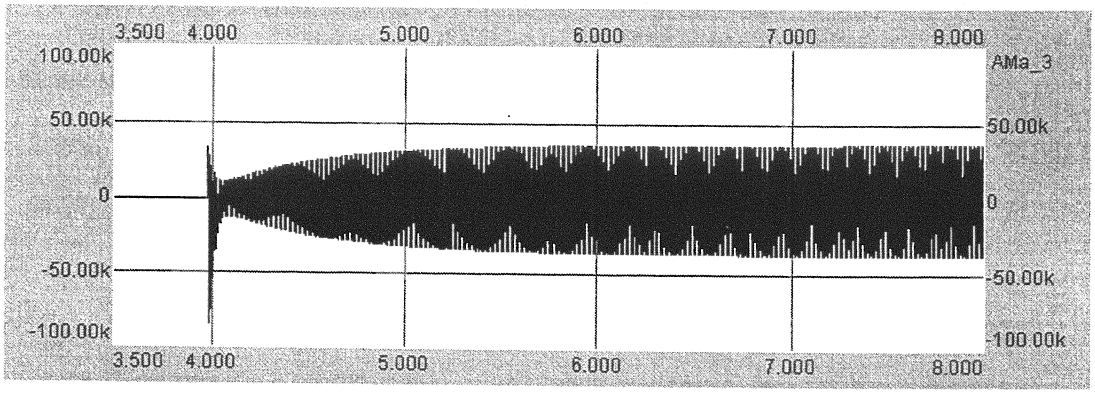
3. Reactive power compensation

(1) Short circuit simulation

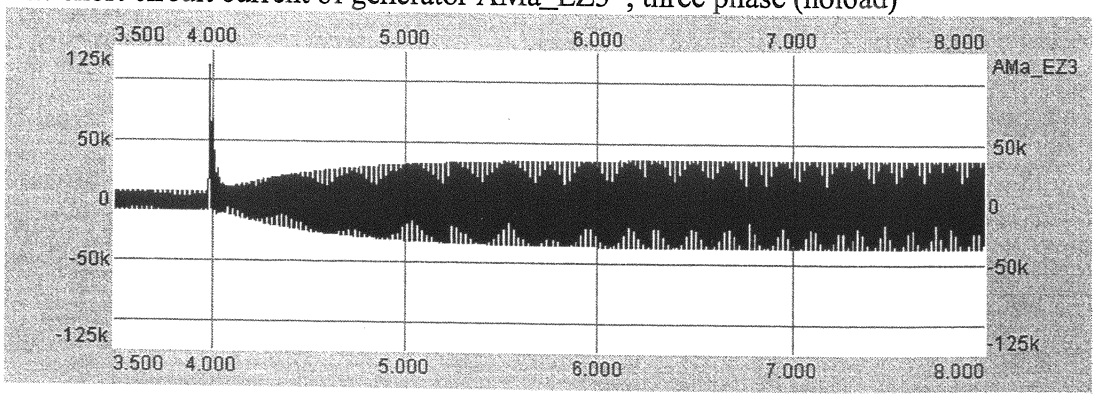


Result: maxium peak current 71KA,
maxium steady current 43KA (nominal current)

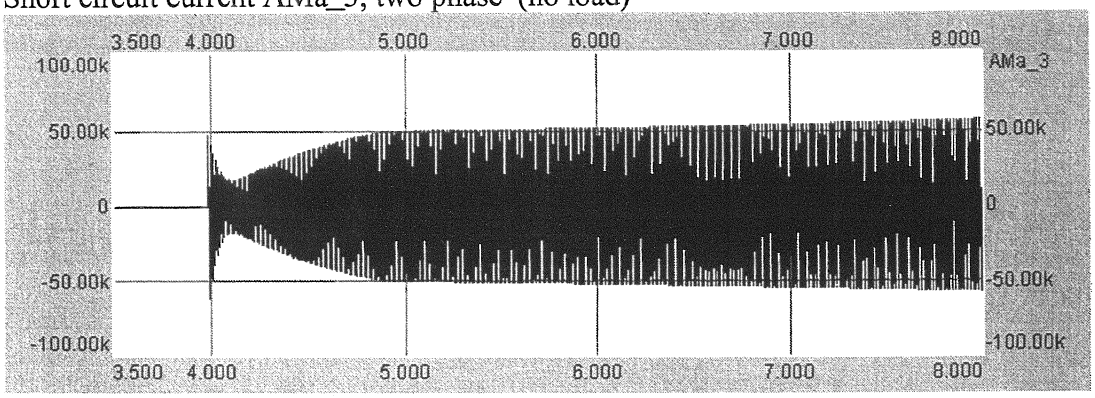
Three phase short circuit current AMa_3



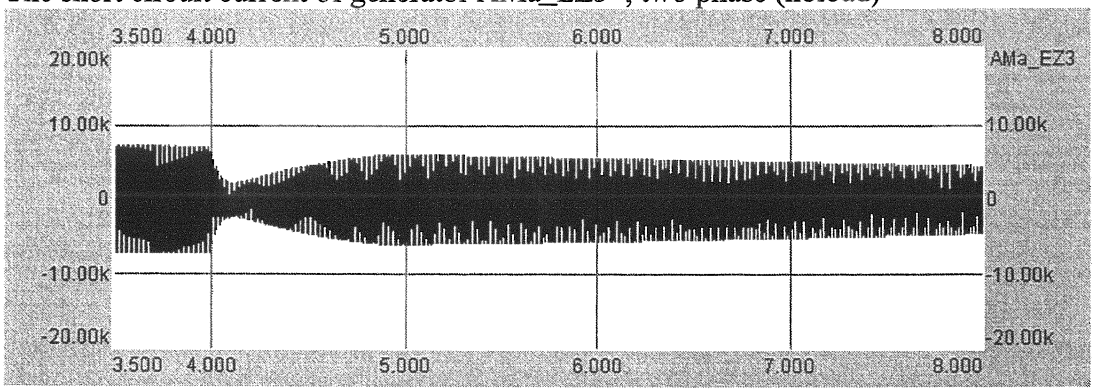
The short circuit current of generator AMa_EZ3 , three phase (noload)



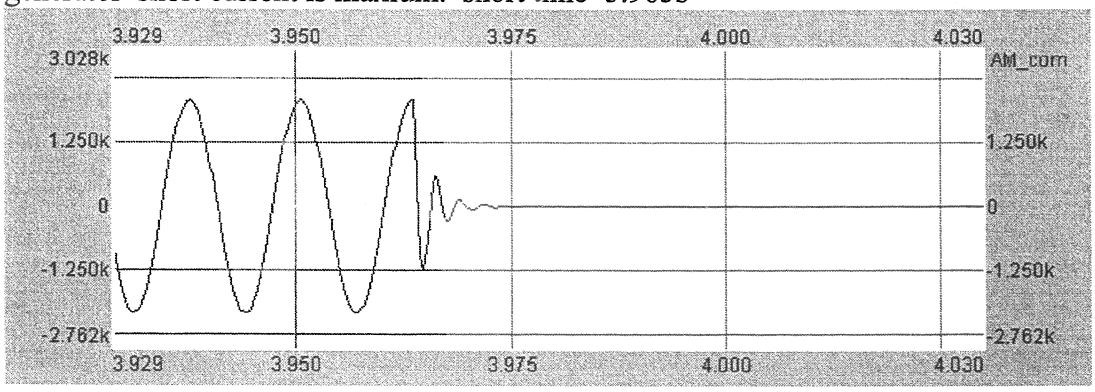
Short circuit current AMa_3, two phase (no load)



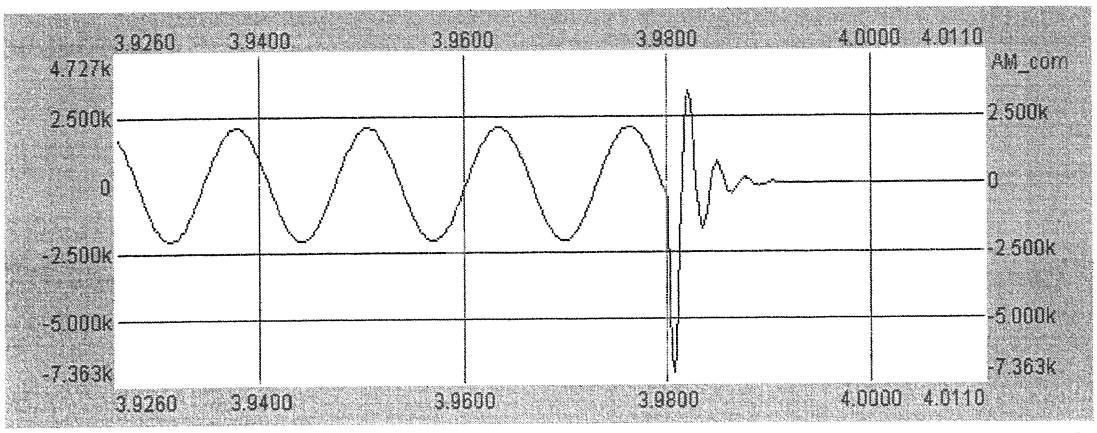
The short circuit current of generator AMa_EZ3 , two phase (noload)



the current in one module (two units) , short angle=0 (voltage), at this time the generator short current is maxium. short time=3.965s



Current in one module (two units), short angle=90 (voltage), then the generator short current is not maxium, short time=3.980



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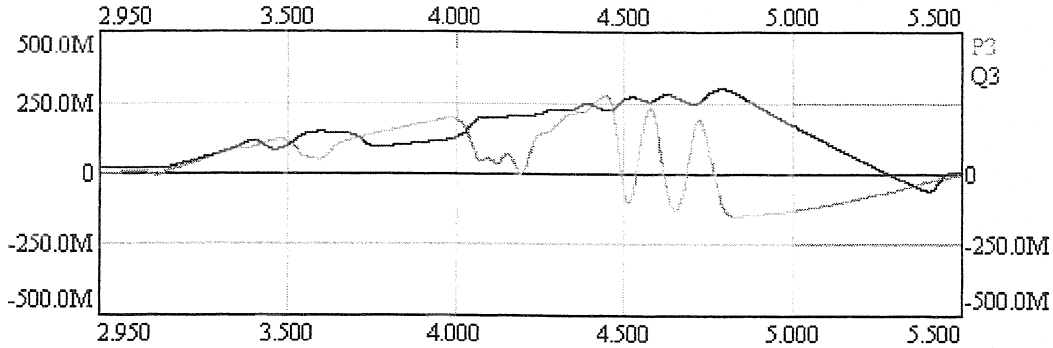
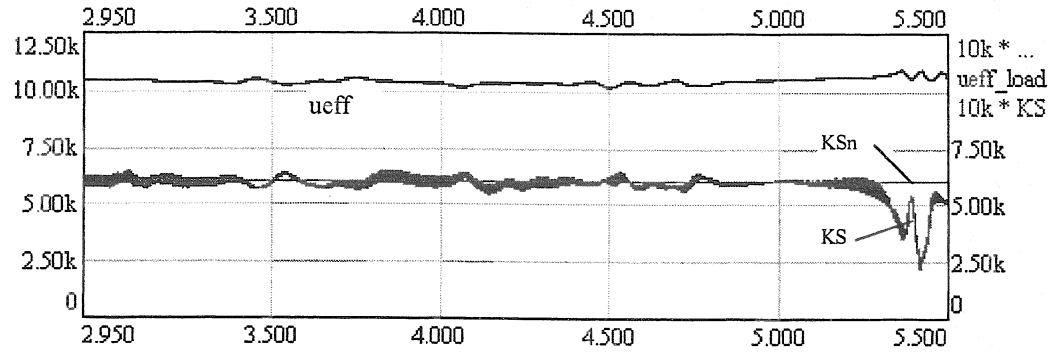
4. Simulations applying filters of different time constant in the signal measurements

Load power

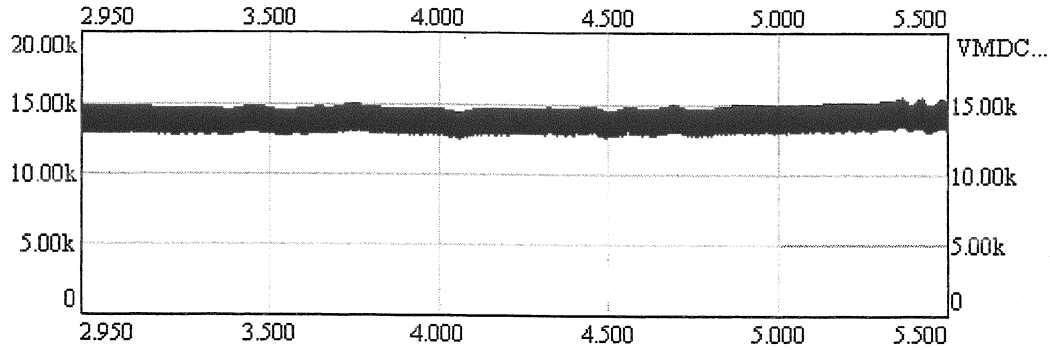


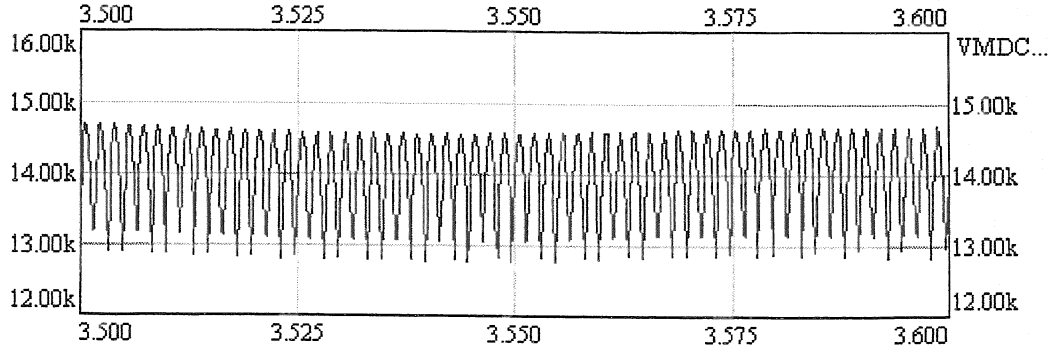
(1) Filter T=0

Voltage and current



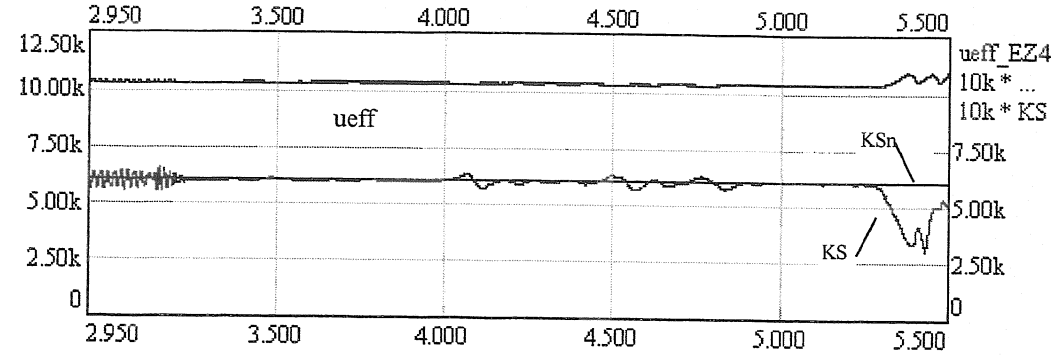
Measurement signal of voltage



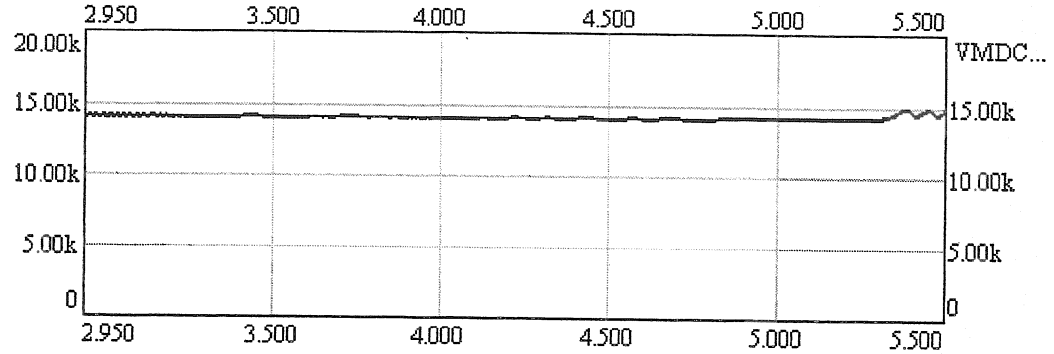


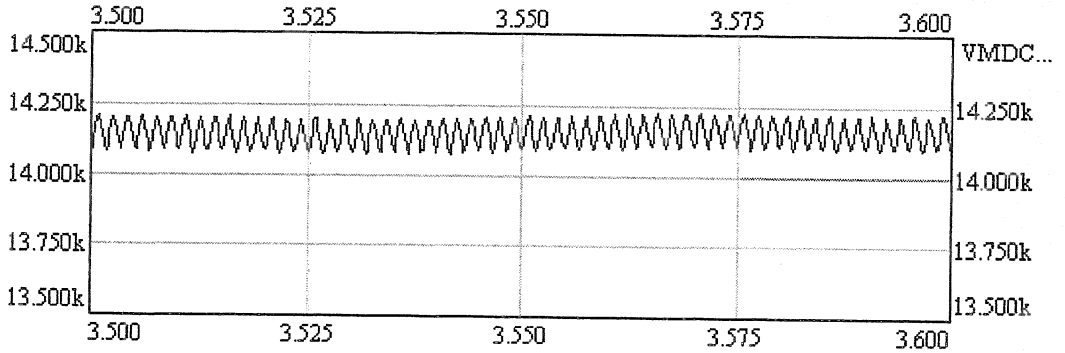
(2) Filter T=2ms

Voltage and power distribution



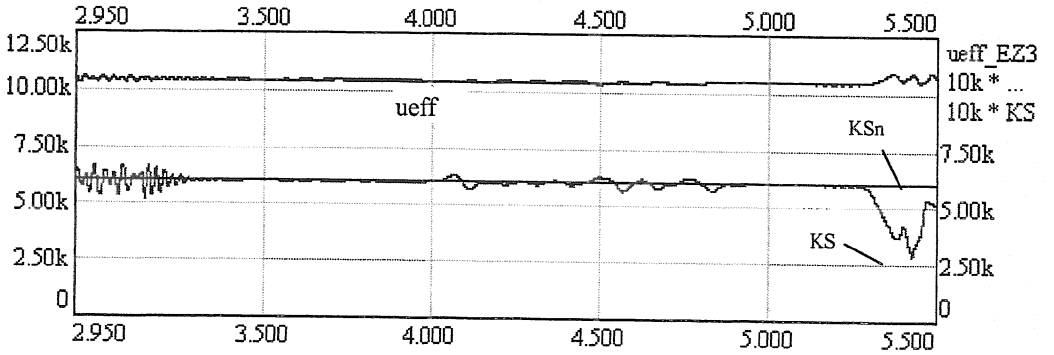
Measurement signal of voltage



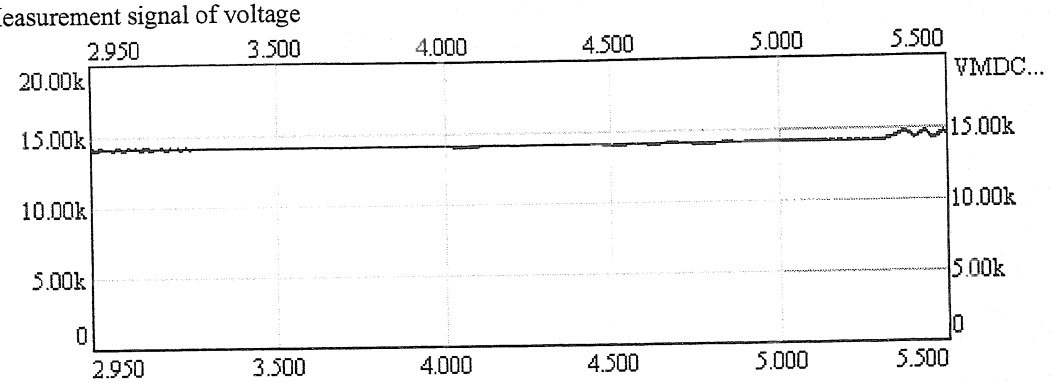


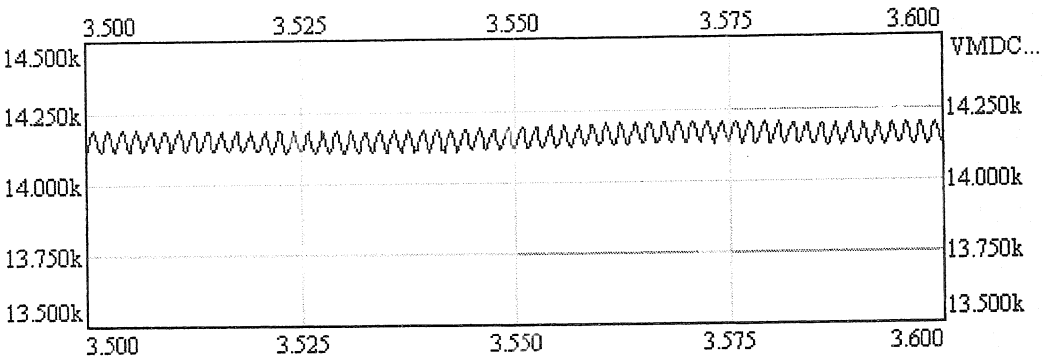
(3) filter t=5ms

Voltage and power distribution



Measurement signal of voltage

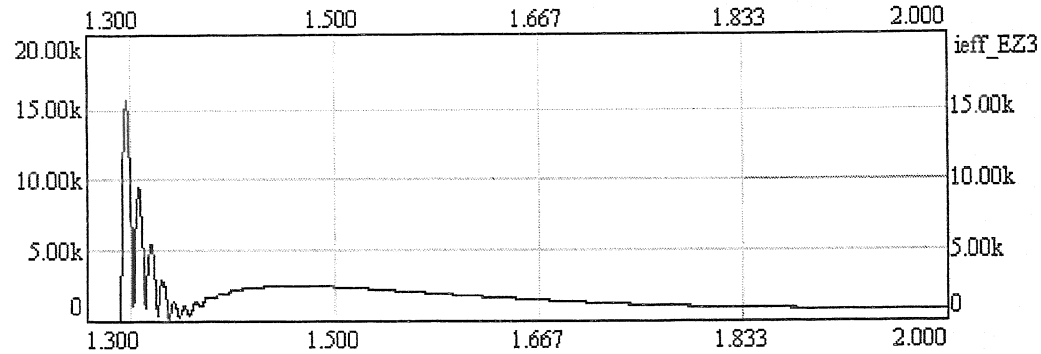




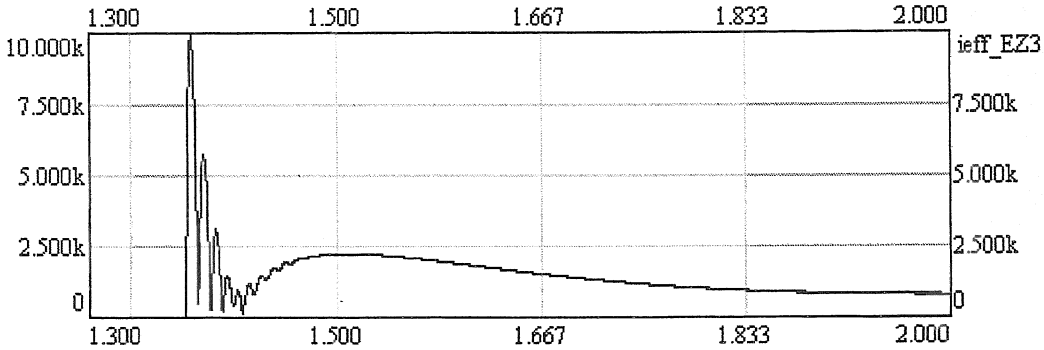
5. The dynamic behaviour of generators during parallel connection

(1) Voltage ueff_EZ3=ueff_EZ4=10.5kV; n3=1505/min, n4=1500/min

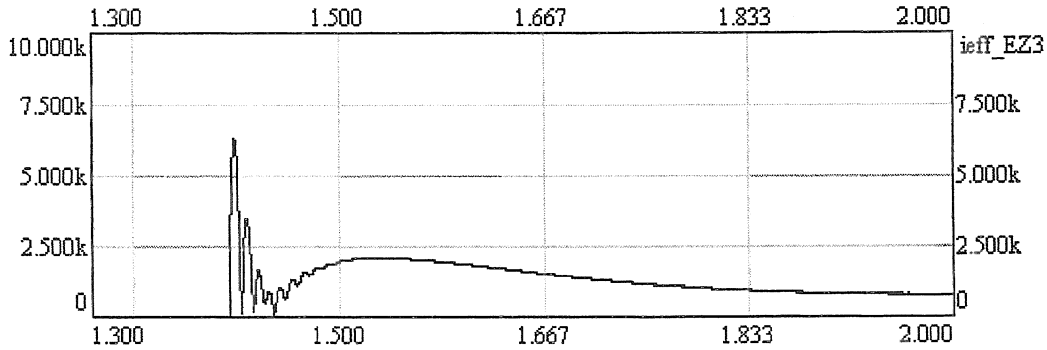
(a) Angle difference=25.2 °, t=1.3251s n3=1505, n4=1500



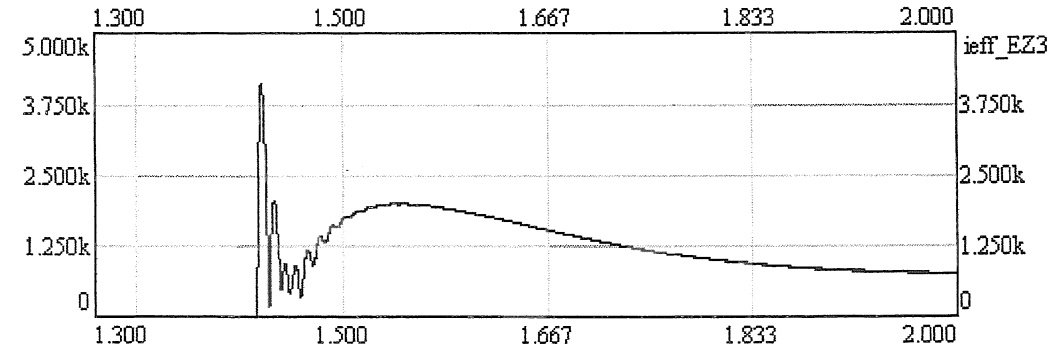
(b) Phase angle difference=15.84° between EZ3 and EZ4 , t=1.377



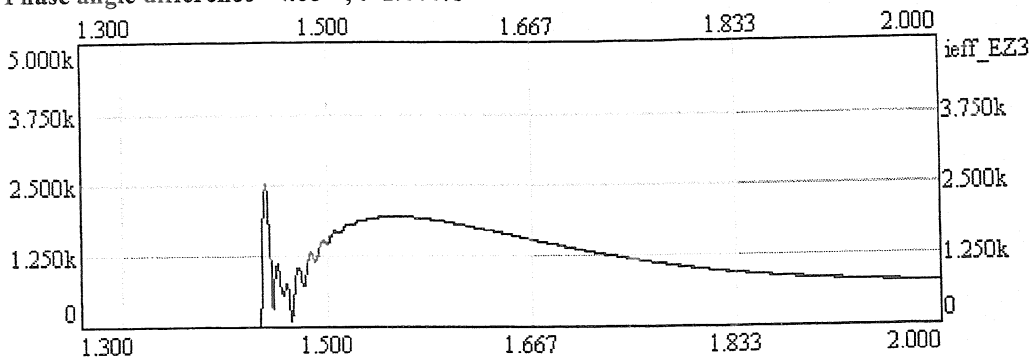
(c) Phase angle difference=10.8°, t=1.41s



(d) Phase angle difference =7.2 ° , t=1.43



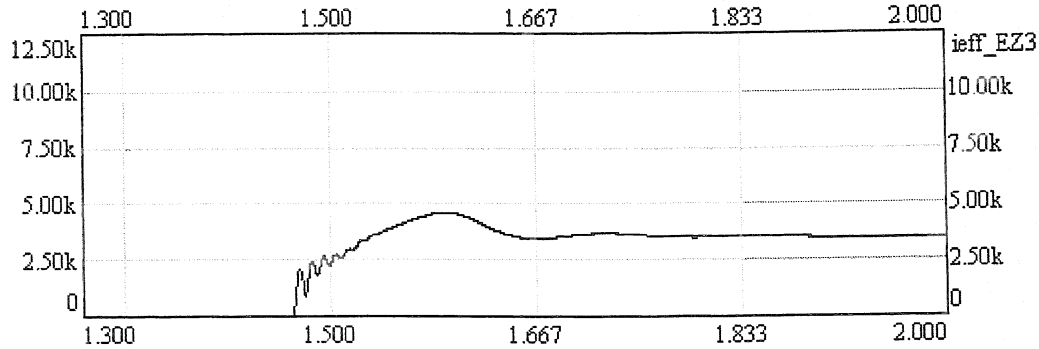
(e) **Phase angle difference =4.68 ° , t=1.4447s**



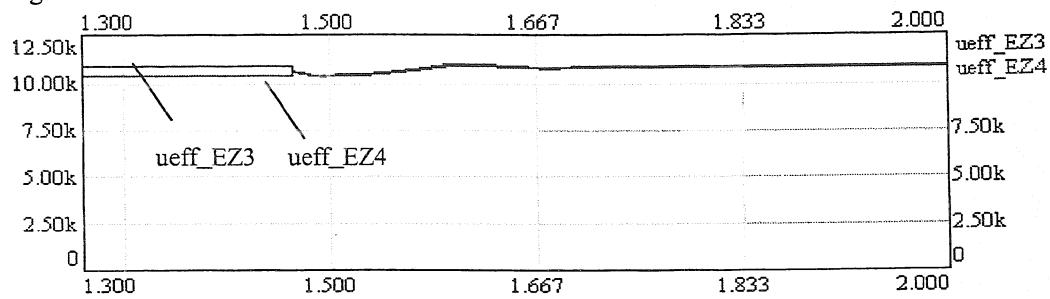
(2) **Phase angle difference=0, n3=1505/min, n4=1500 /min**

(a) **ueff_EZ3=11kV, ueff_EZ4=10.5kV**

Generator current

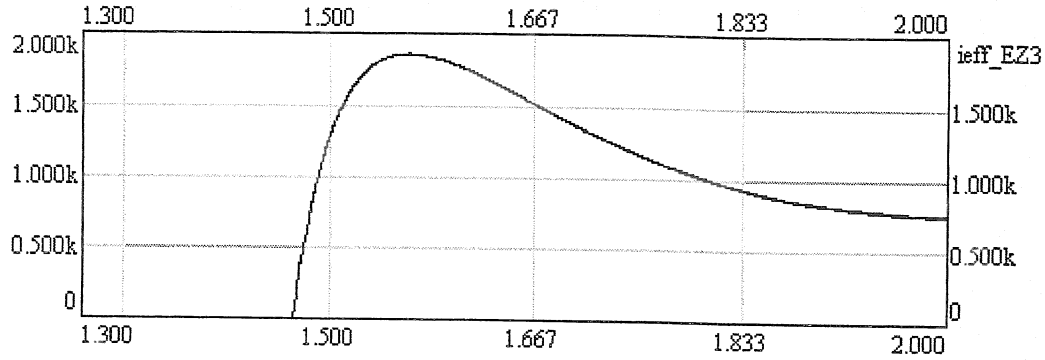


Voltage

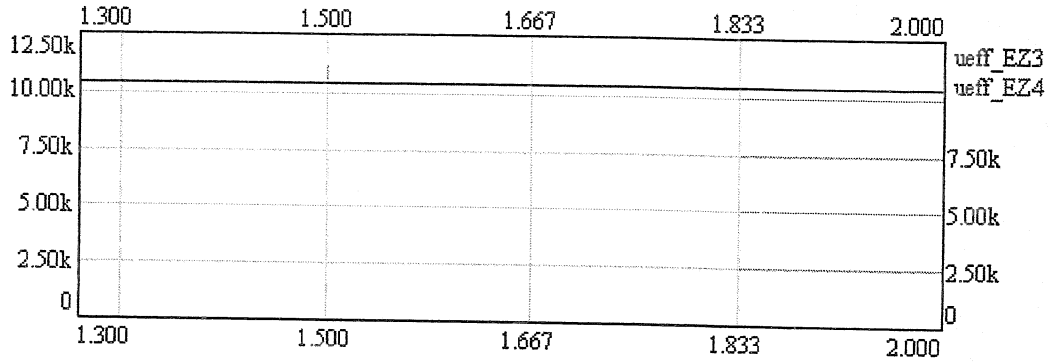


(b) ueff_EZ3=ueff_EZ4=10.5kV

Generator current



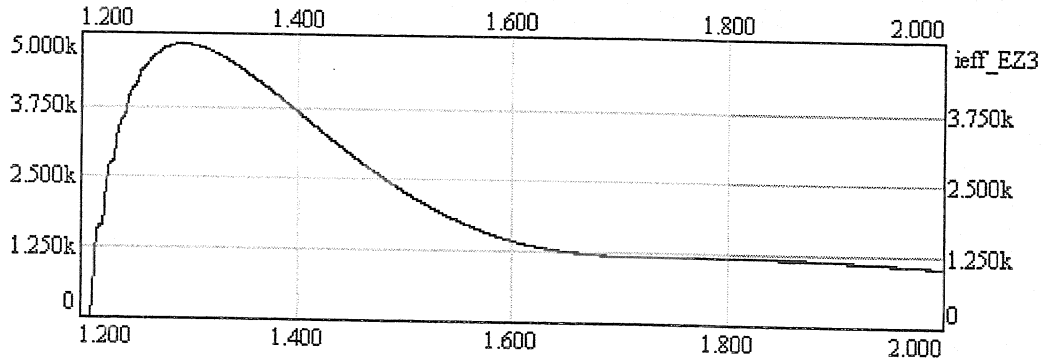
Voltage



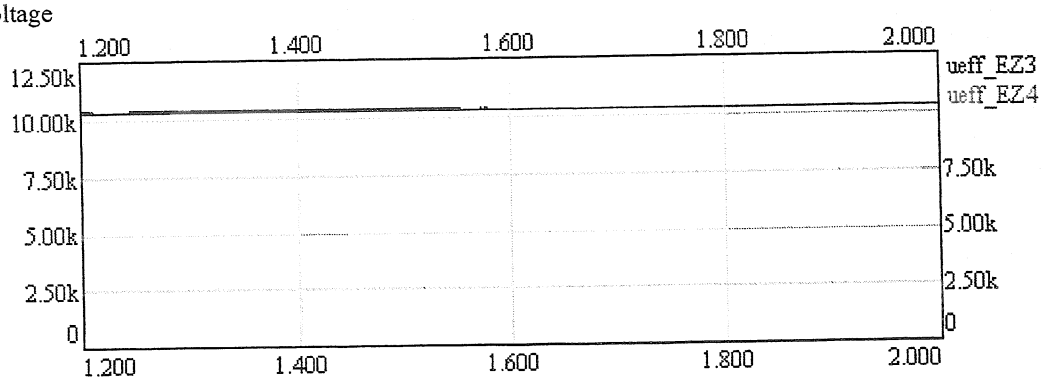
(3) Voltage ueff_EZ3=ueff_EZ4=10.5kV, phase angle difference=0,

(a) n3=1480/min, n4=1500/min, t=1.206s

Generator current

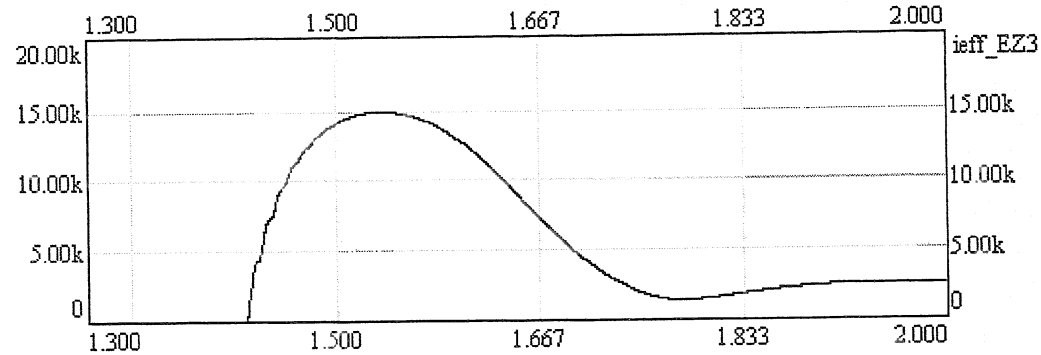


Voltage

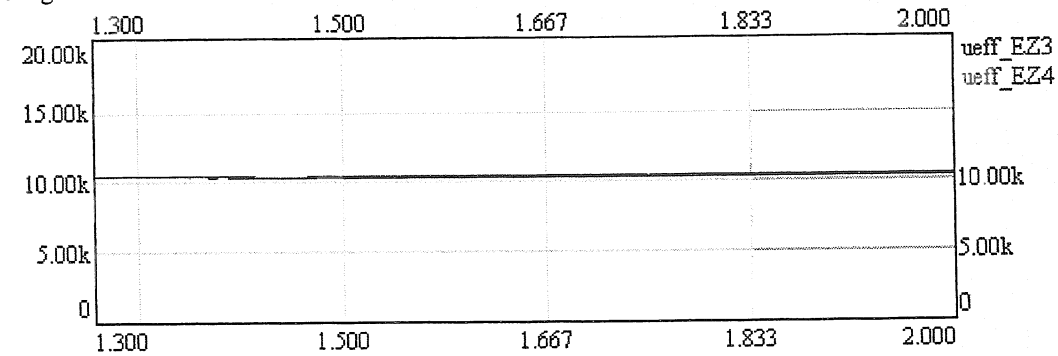


(b) n3=1450/min, n4=1500/min

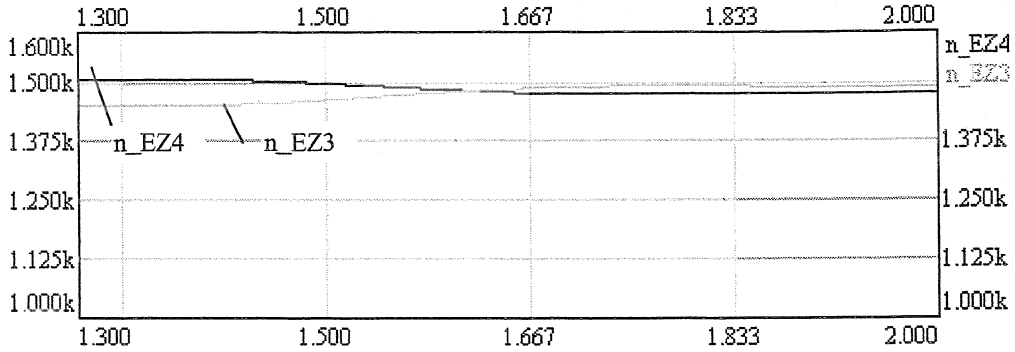
Generator current



Voltage



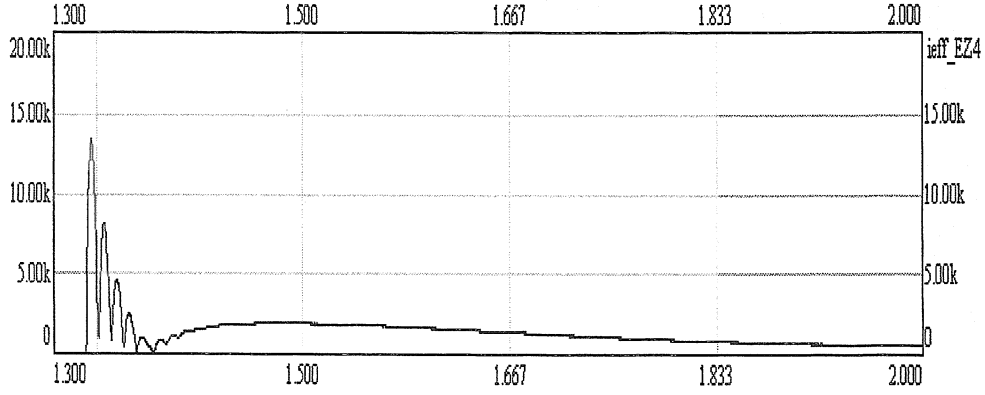
Rotational speed



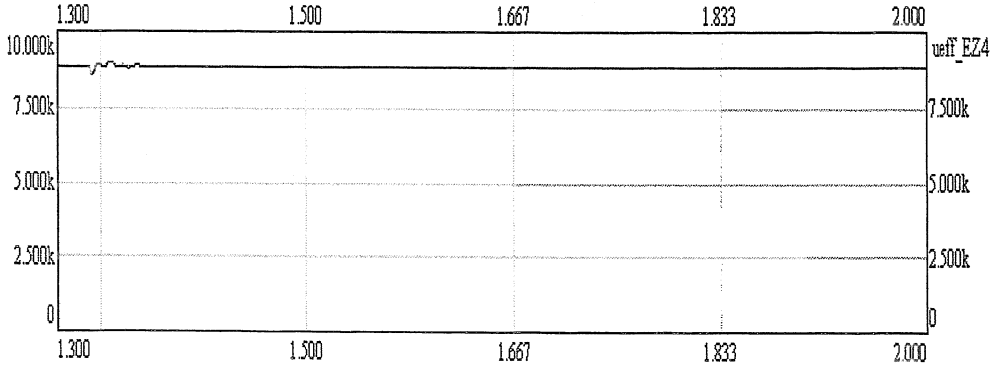
(4) Generators Connect on voltage 9kV

(a) Phase angle difference=25.2 °, t=1.3251s n3=1505, n4=1500

Current

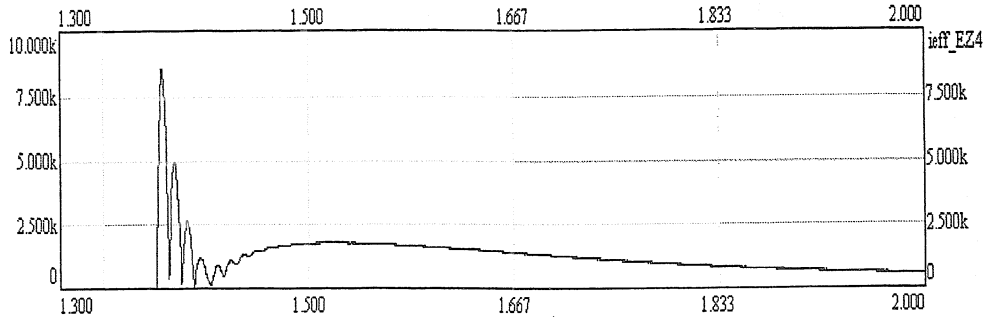


Voltage

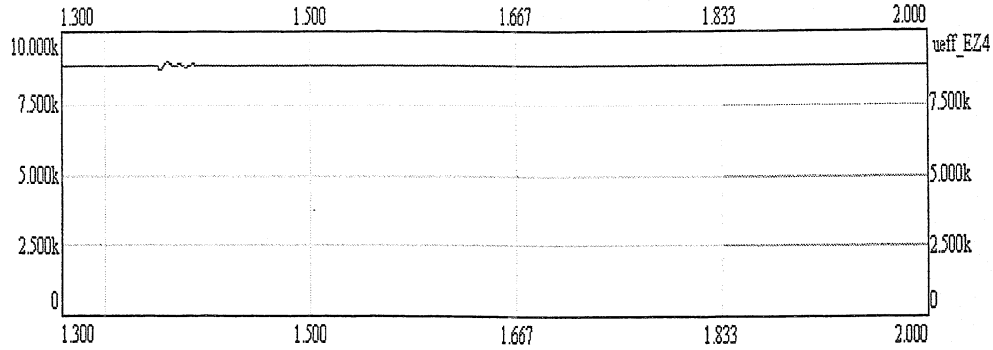


(b) Phase angle difference=15.84° between EZ3 and EZ4 , t=1.377

C urrent

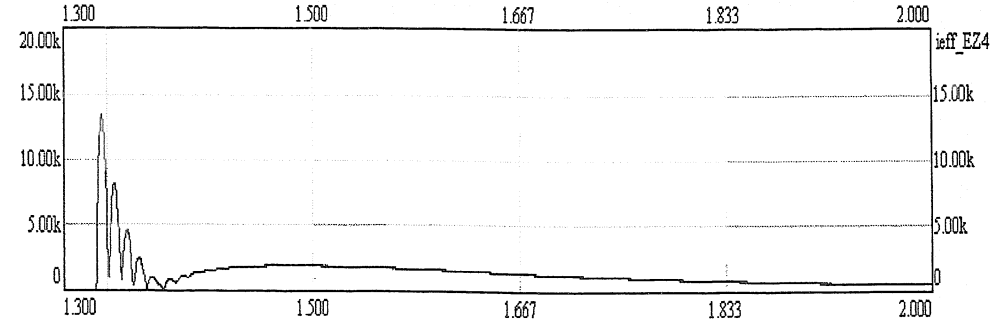


Voltage

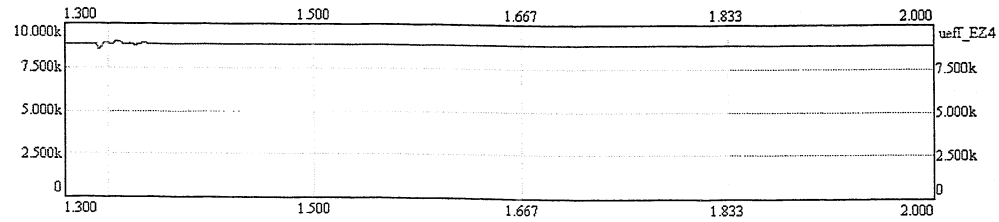


(3) Phase angle difference=10.8°, t=1.41s

Current

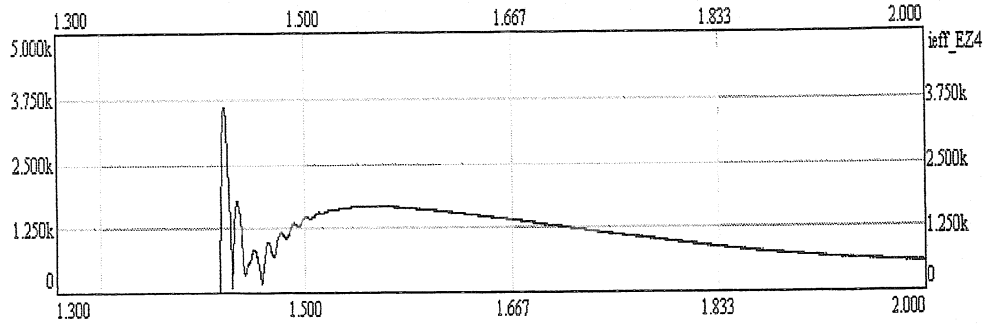


Voltage

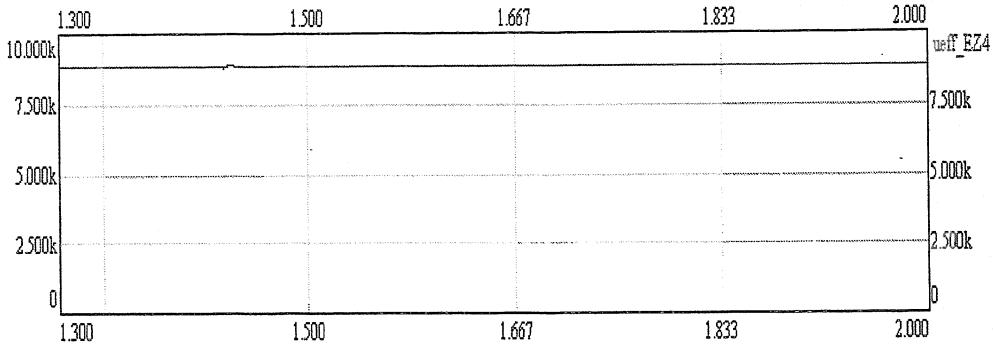


(4) Phase angle difference =7.2 ° , t=1.43

Current

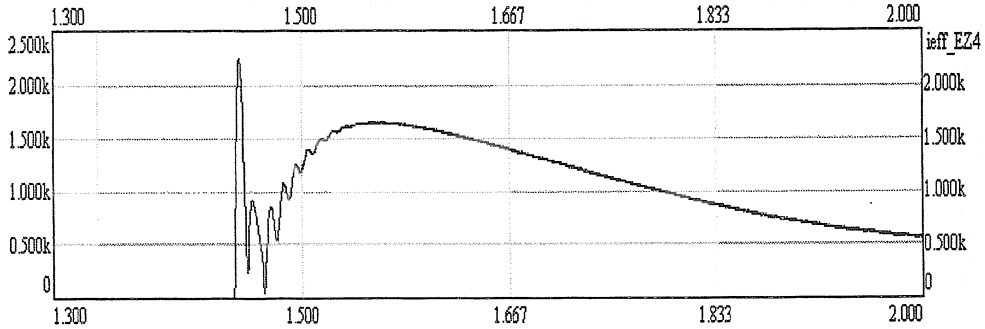


Voltage

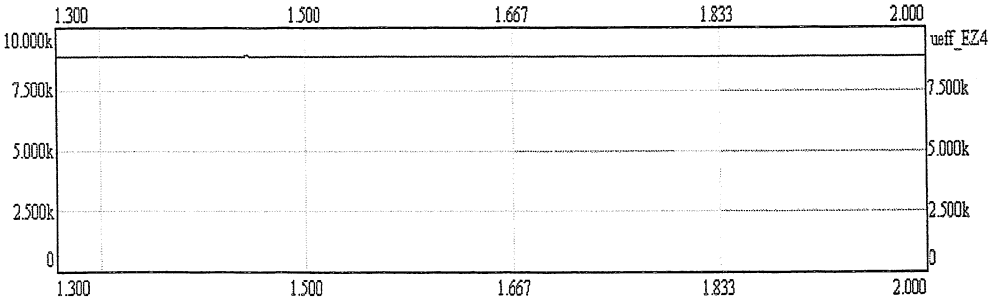


(5) Phase angle difference =4.68 ° , t=1.4447s

Current

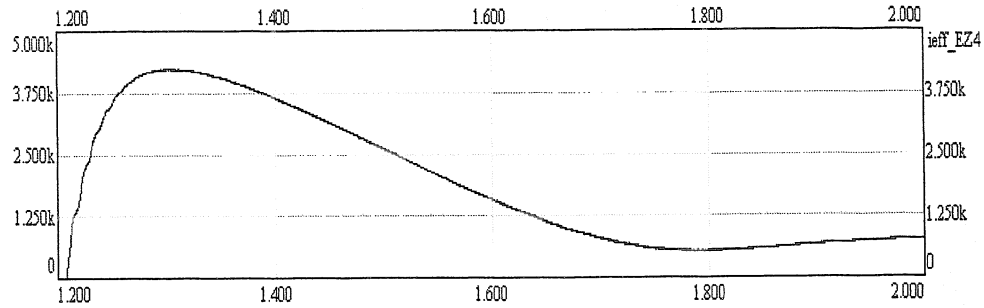


Voltage

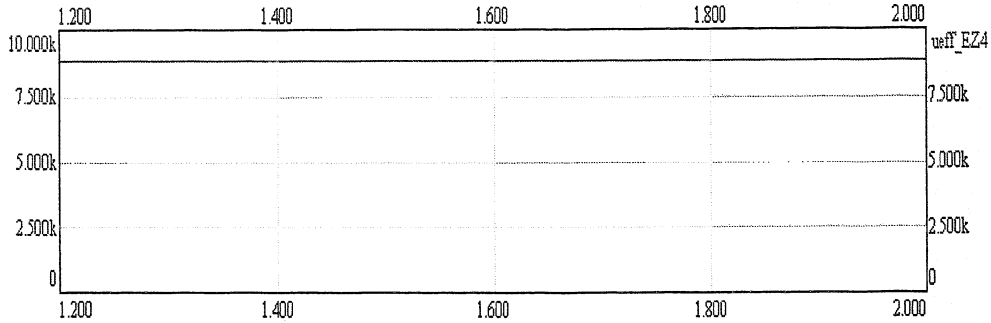


(6) n3=1480/min, n4=1500/min, t=1.206s

Current



Voltage



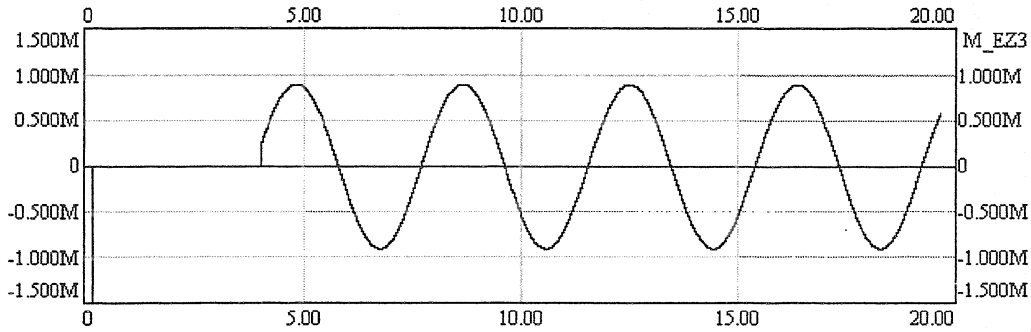
6. Parametrical studies performed for varying machine parameters

Note: (1) The torque is applied at EZ3, the next torque print-curve is its electromagnetic output, so the frequency is 4 times higher than its mechanical frequency.
(2) The stator current is apparent , so it is positive all time.

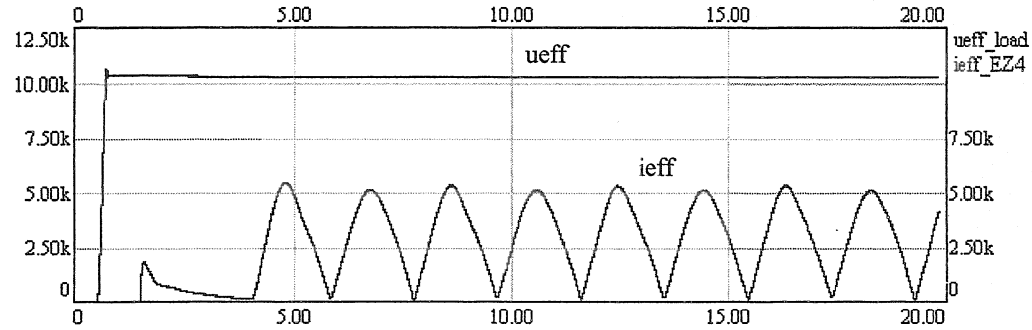
(1) Normal parameters

(a) f= 0.065Hz (mechanical), torque = 8e+5Nm

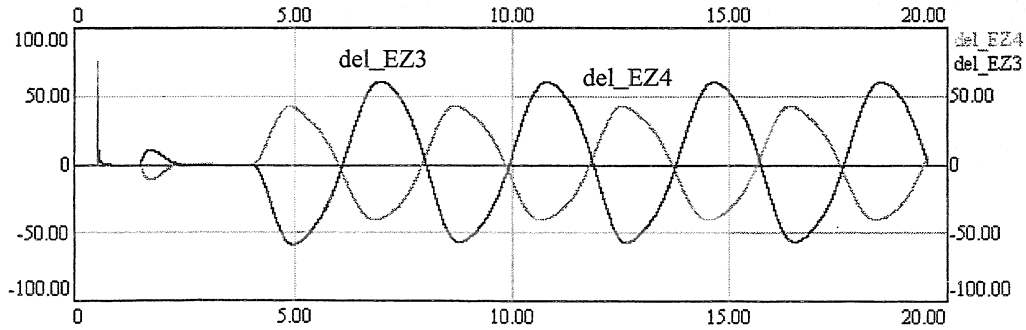
Torque (f=.065Hz)



Current and voltage (f=0.065Hz)

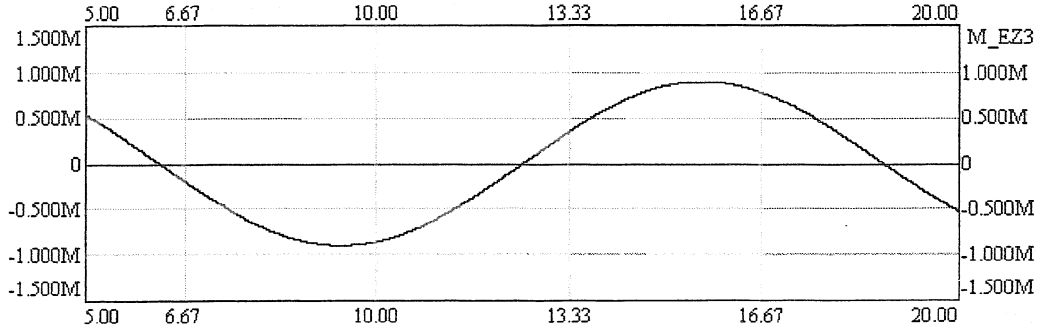


Angle (f=0.065Hz)

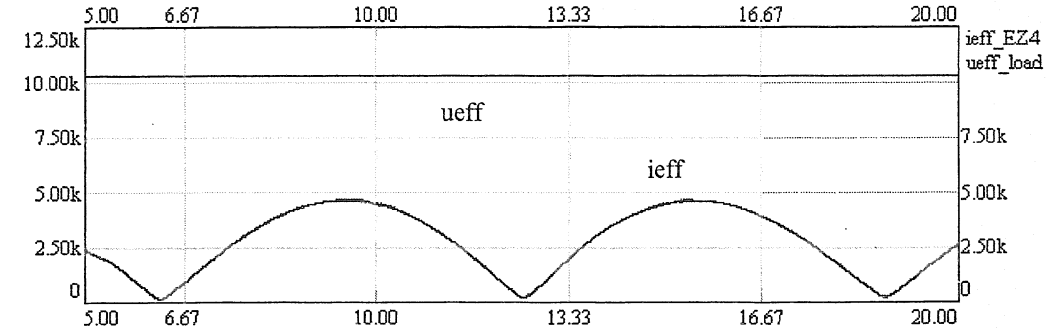


(b) f=0.02Hz (mechanical) , torque = 8e+5Nm

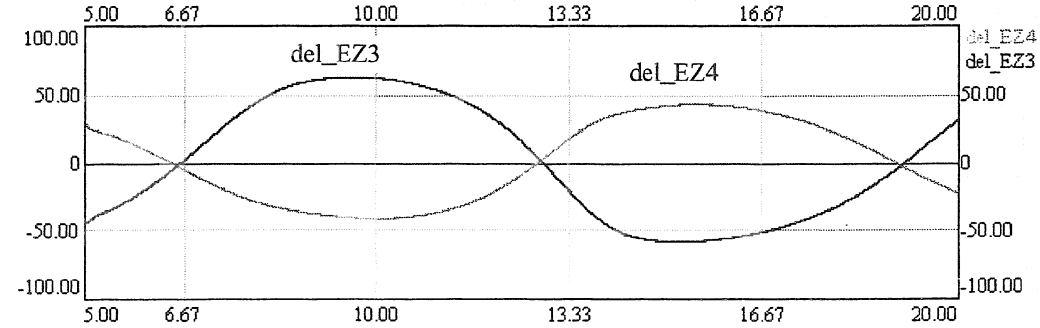
Torque



Voltage and current

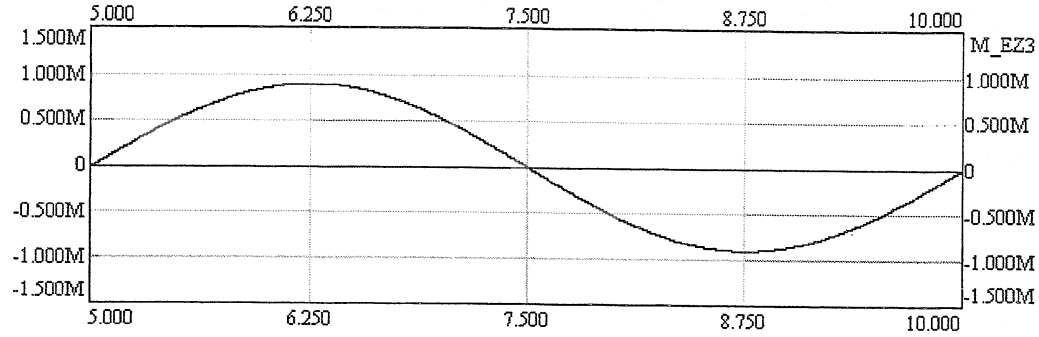


Rotor angles

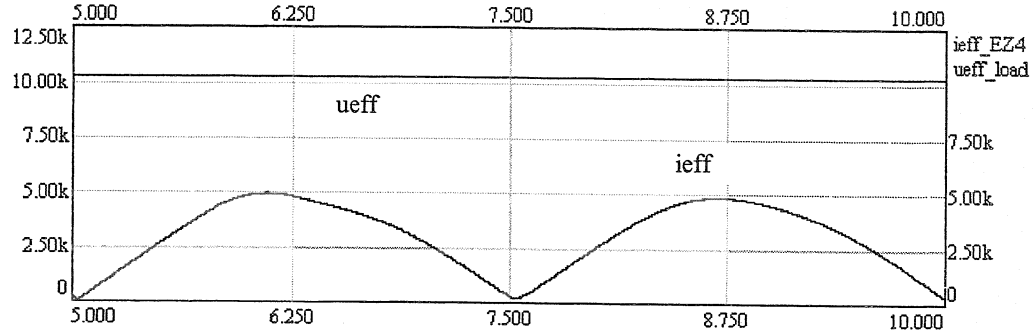


(c) f=0.05Hz, torque = 8e+5Nm

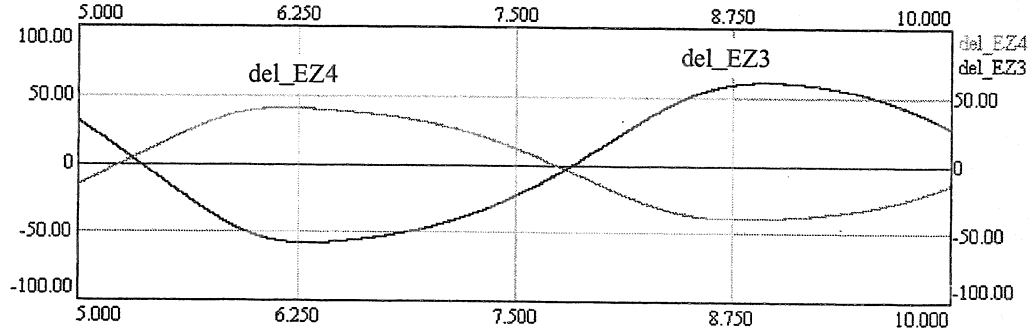
Torque f=0.05 Hz (mechanical)



Voltage and current f=0.05 Hz (mechanical)

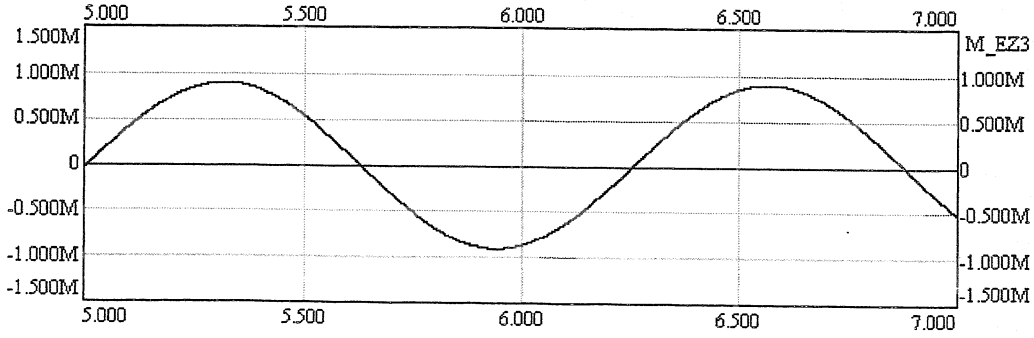


Rotor angle f=0.05 Hz (mechanical)

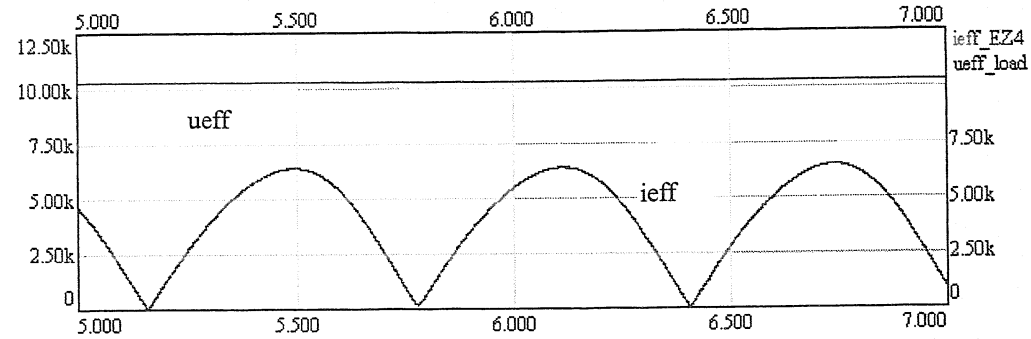


(d) f=0.2Hz, torque = 8e+5Nm

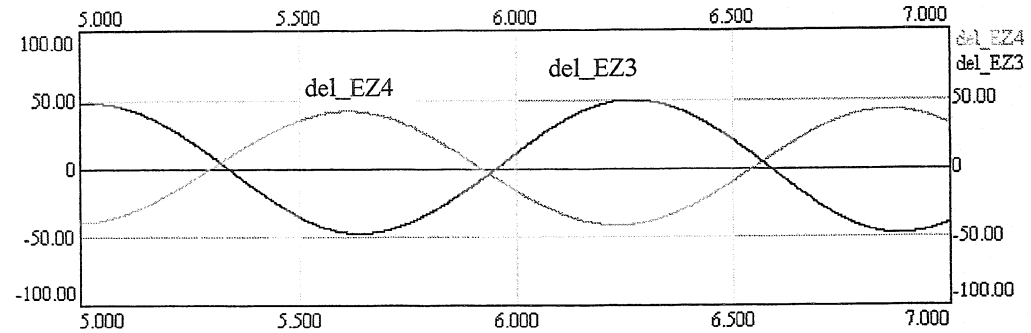
Torque



Voltage and current

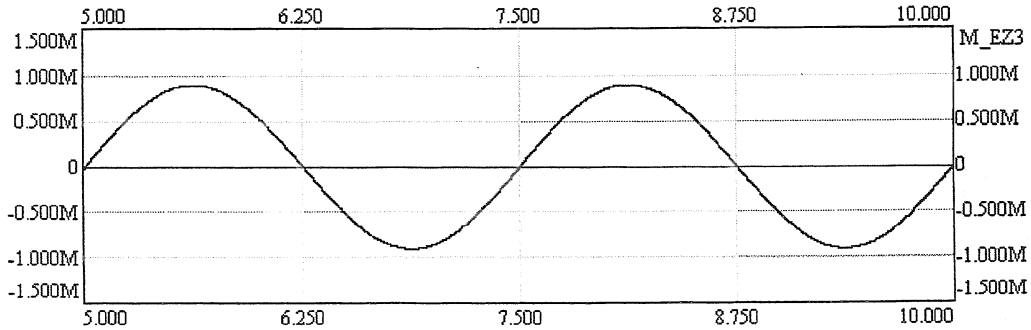


Rotor angles

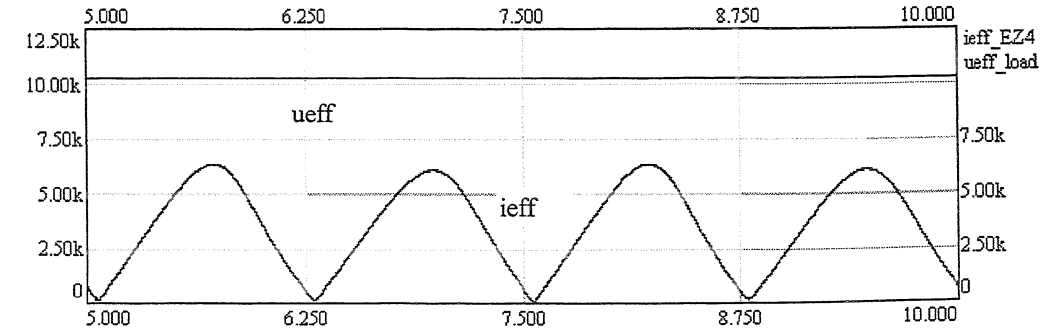


(e) f=0.1hz (mechanical), torque = 8e+5N.m

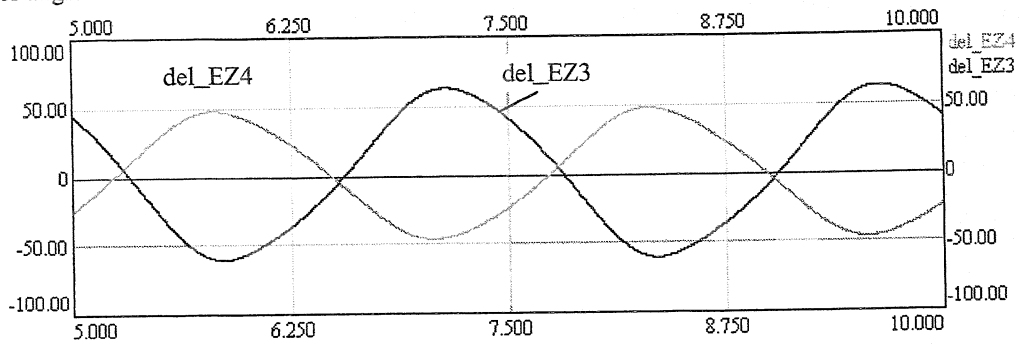
Torque applied in EZ3 (electrical frequence 0.4hz corresponds to in mechanical frequence 0.1hz)



Voltage and current , f=0.1hz

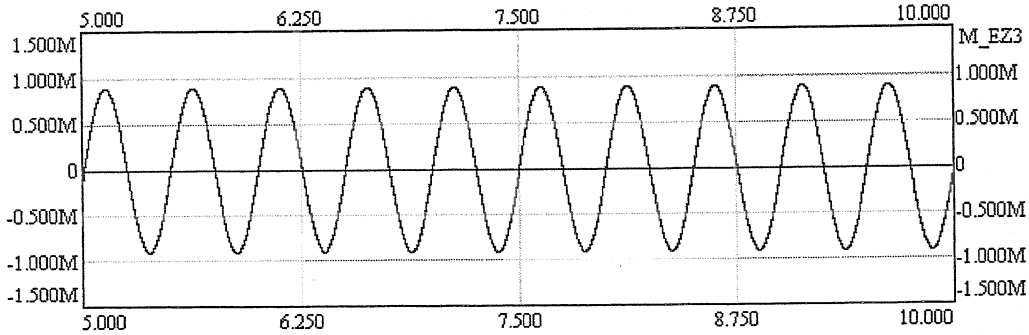


Rotor angle of EZ3 and EZ4

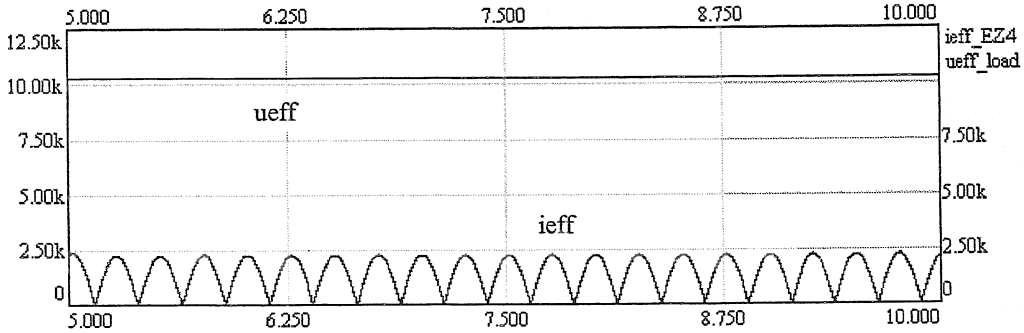


(f) f=0.5hz (mechanical), torque = 8e+5N.m

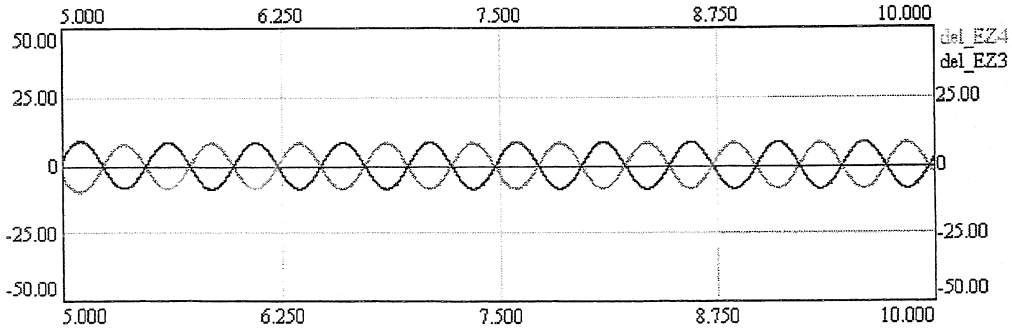
Torque applied in EZ3 , f=0.5hz (mechanical)



Voltage and current , f=0.5

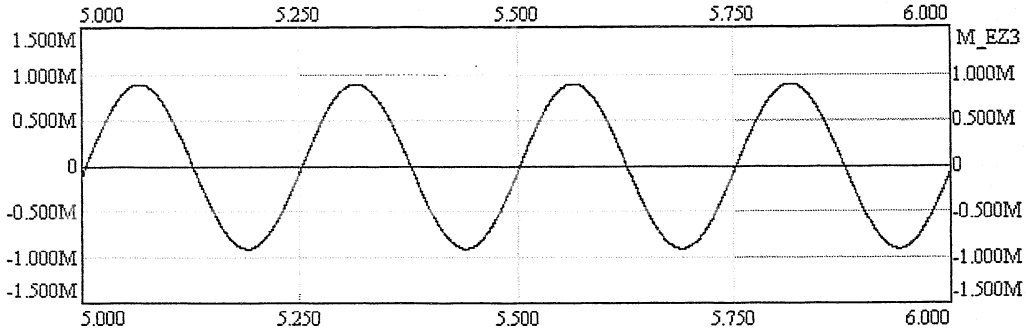


Rotor angle, torque f=0.5hz

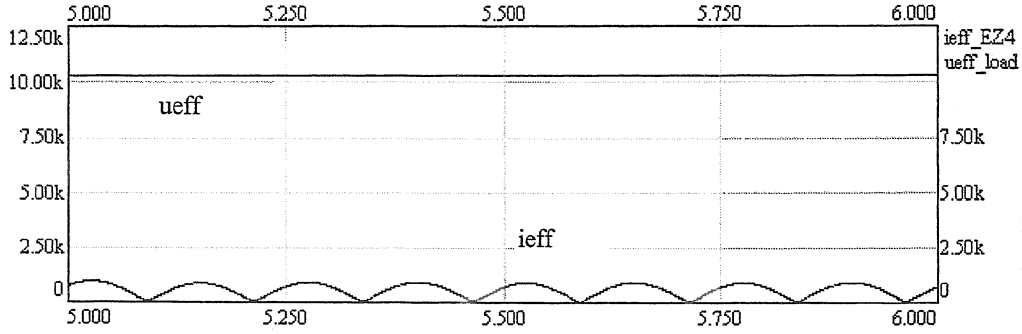


(g) f=1.0hz (mechanical), torque = 8e+5N.m

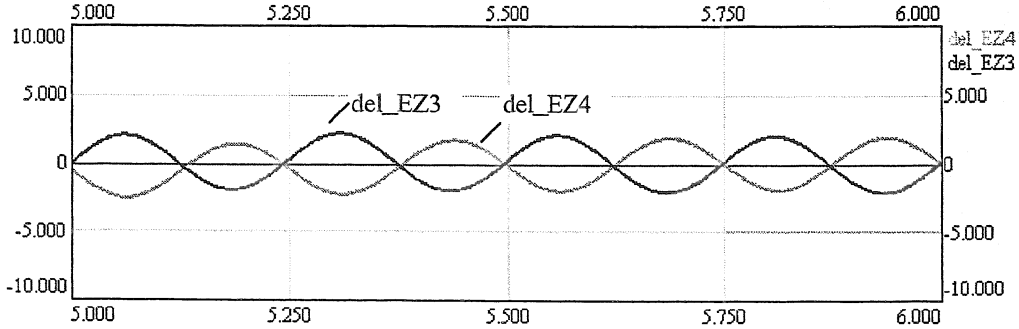
Torque f=1.0hz(mechanical)



Voltage and current in f=1.0hz(mechanical)

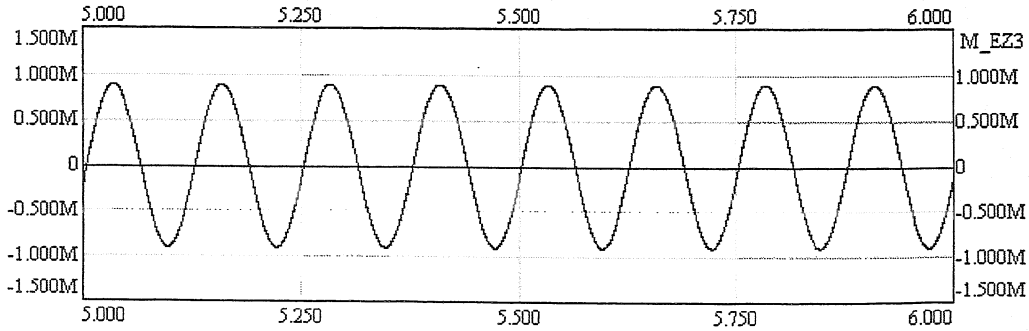


Rotor angle, f=1.0hz(mechanical)

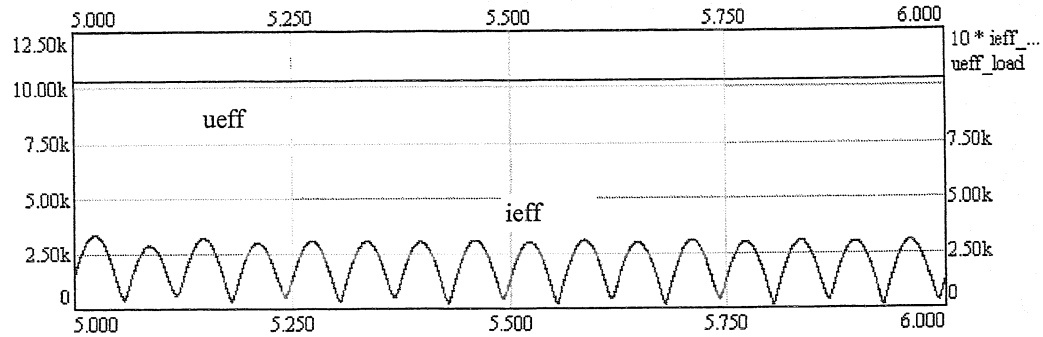


(h) f=2.0hz (mechanical), torque = 8e+5N.m

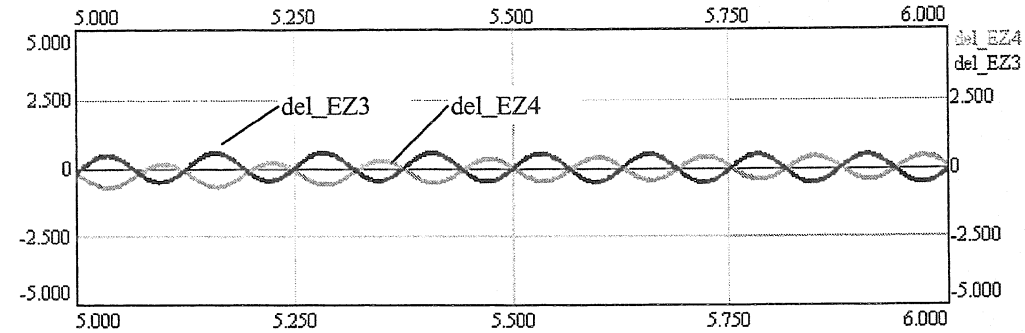
Torque applied in EZ3



Voltage, current

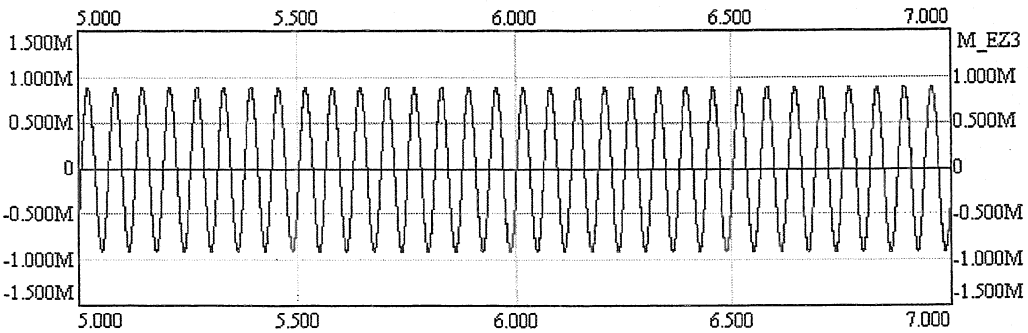


Rotor angle of EZ3and EZ4

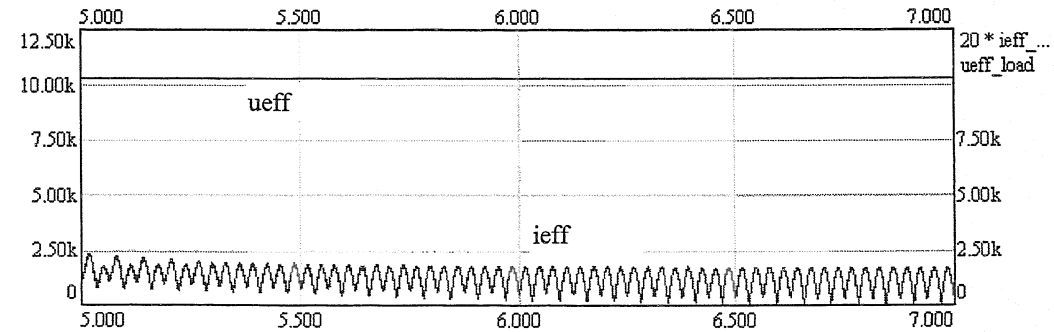


(i) f=4.0hz (mechanical), torque = 8e+5N.m

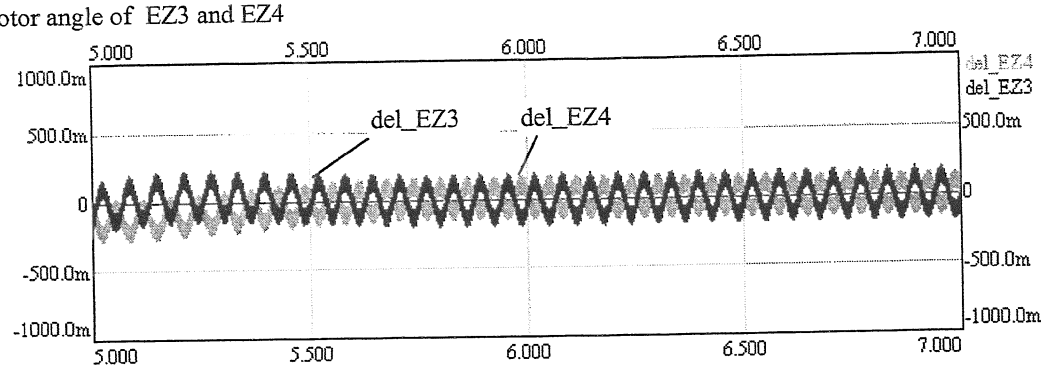
Torque



Voltage and current of bus

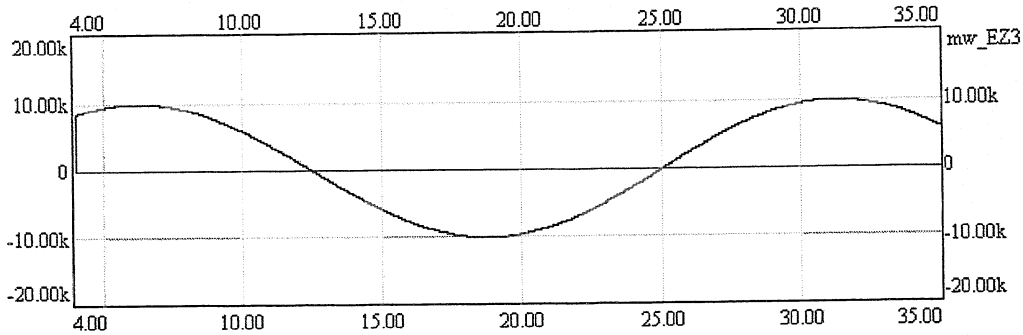


Rotor angle of EZ3 and EZ4

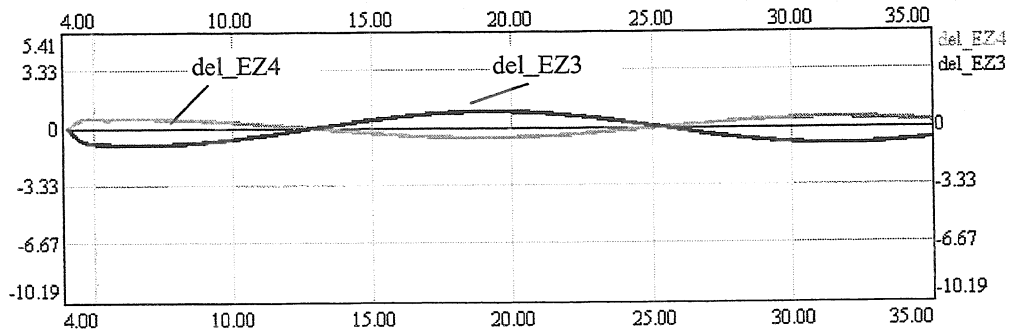


(j) f=0.01Hz, T=1.0e+4N.m

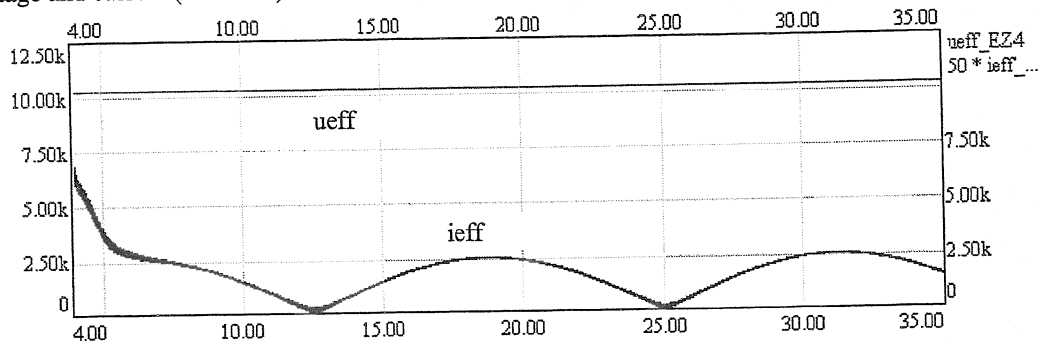
Torque (f=0.01hz)



Angle (f=0.01hz)

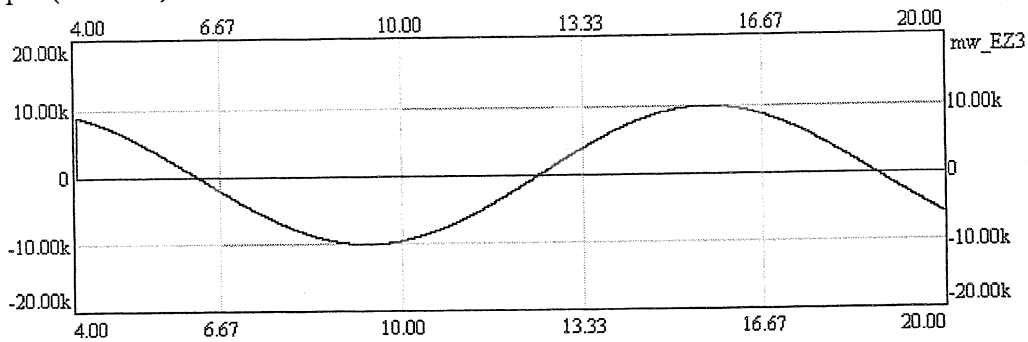


Voltage and current (f=0.01hz)

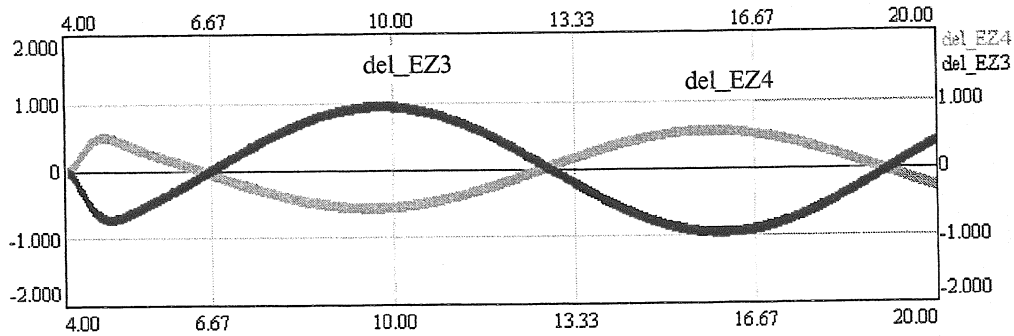


(k) f=0.02Hz , T=1.0e+4N.m

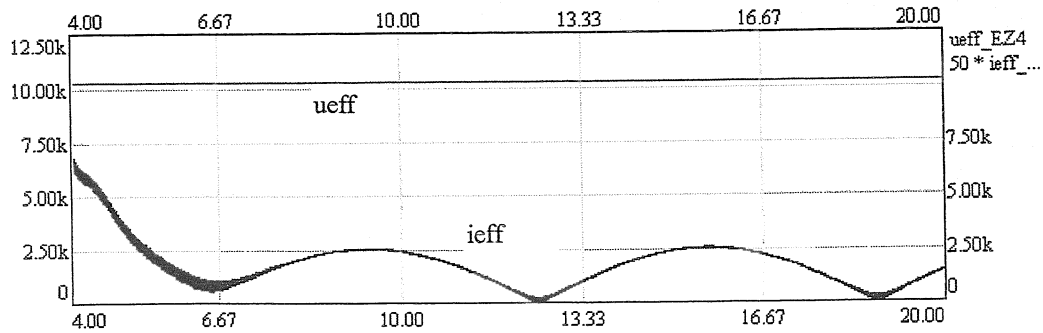
Torque (f=0.02Hz)



Angle (f=0.02Hz)

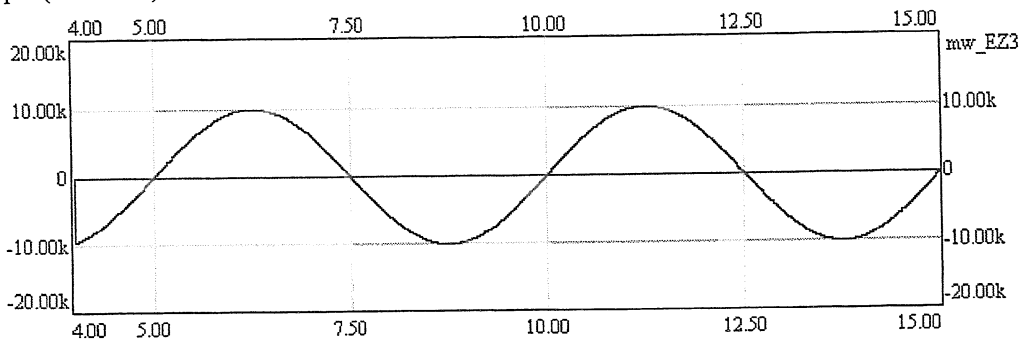


Voltage and current (f=0.02Hz)

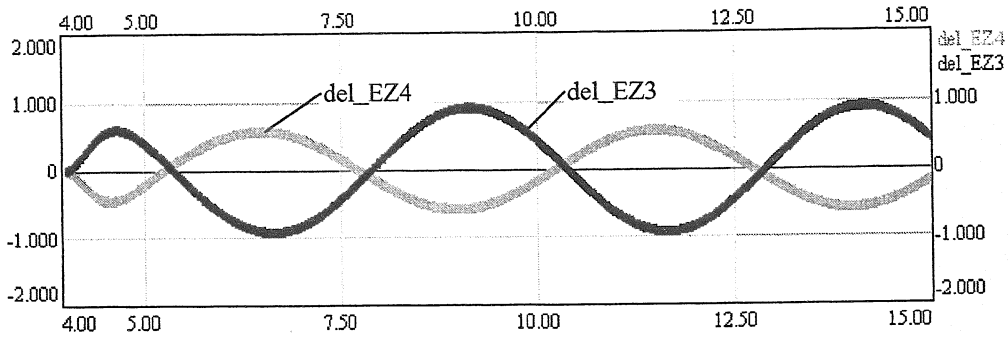


(L) f=0.05HZ, T=1.0e+4N.m

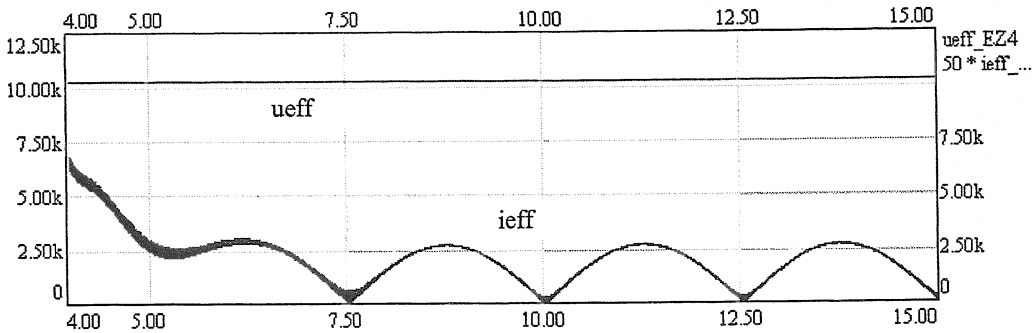
Torque (f=0.05Hz)



Angle (f=0.05Hz)

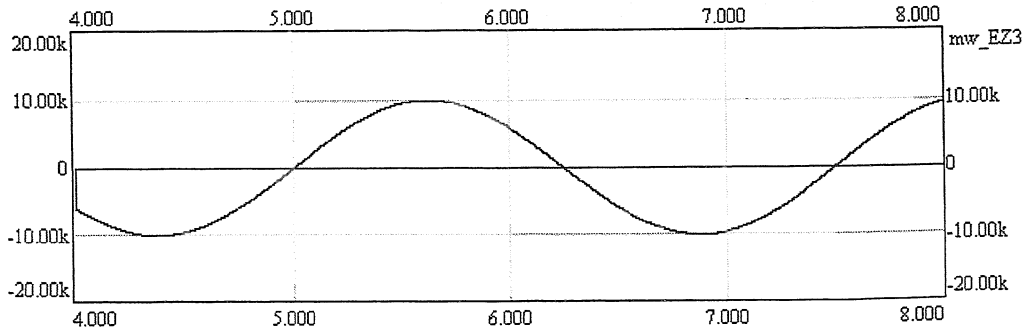


Voltage and current (f=0.05Hz)

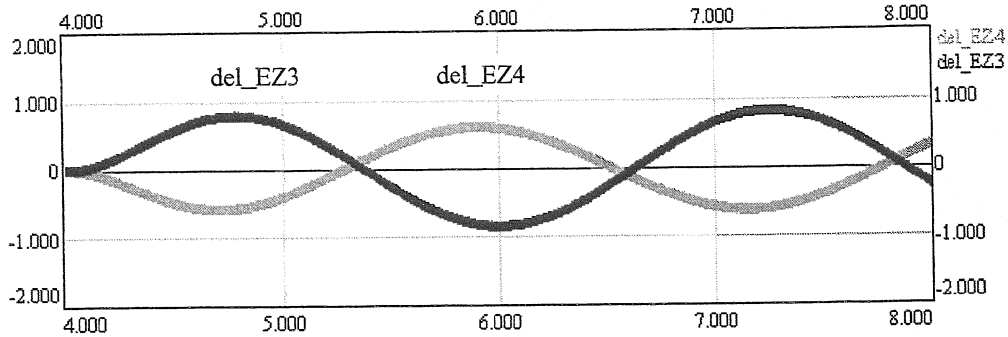


(N) f=0.1HZ, T=1.0e+4N.m

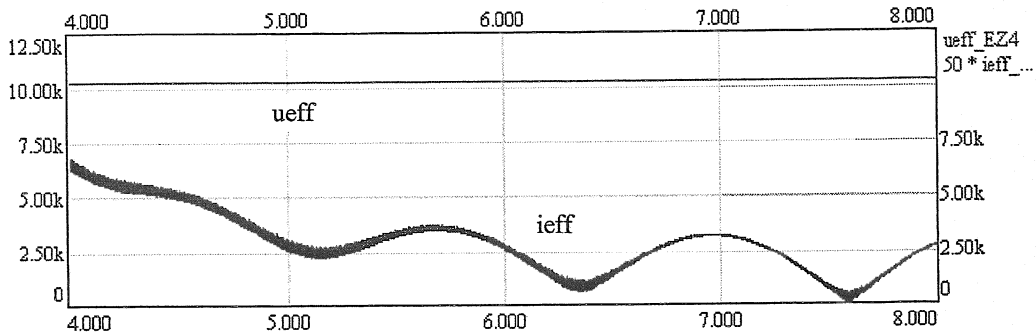
Torque (f=0.1hz, T=1.0e+4)



Angle(f=0.1hz, T=1.0e+4)

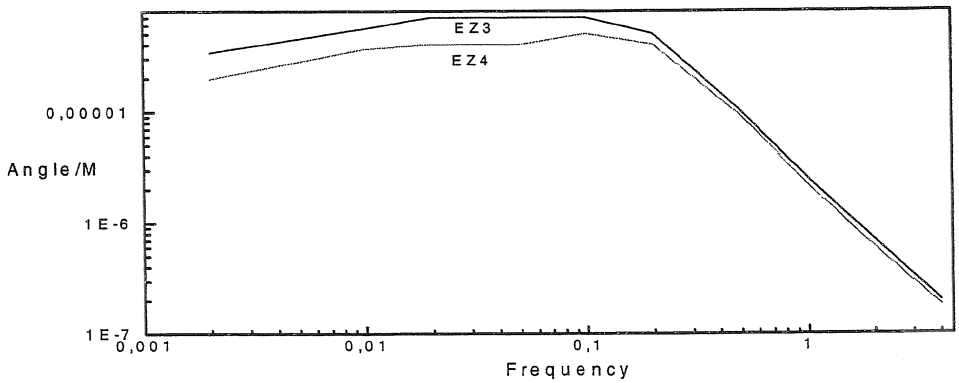


Voltage (f=0.1hz, T=1.0e+4)

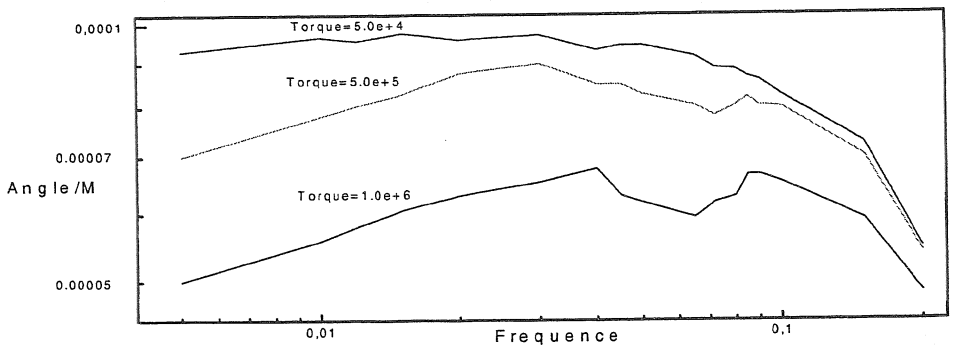


Rotor Angle/Torque as a Function of Frequence

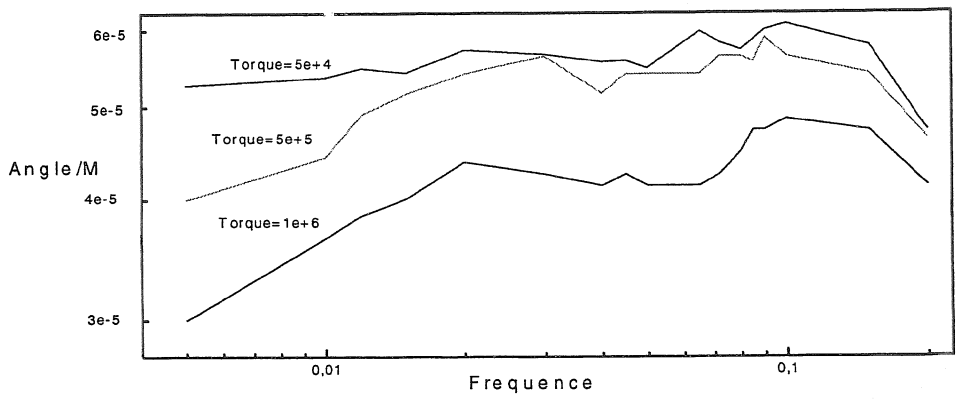
(T=8.0e+5N.m)



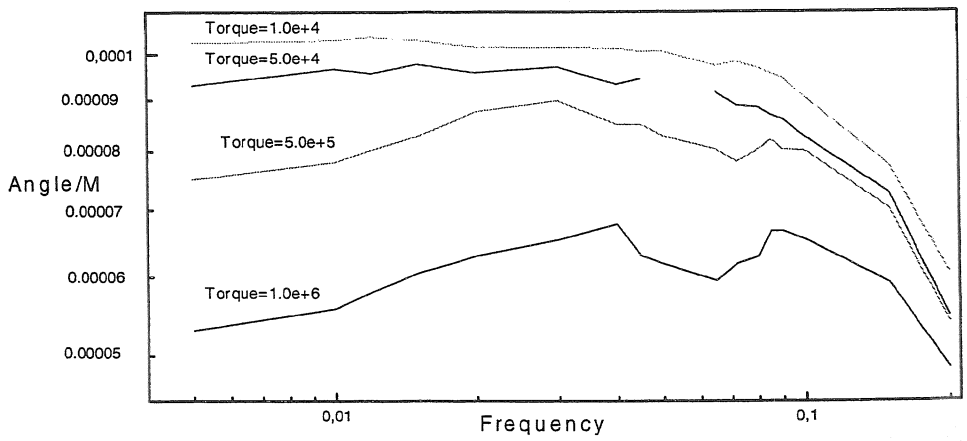
EZ3


0,0001
0.00007
0.00005
Angle/M
Torque=5.0e+4
Torque=5.0e+5
Torque=1.0e+6
0,01
Frequence
0,1

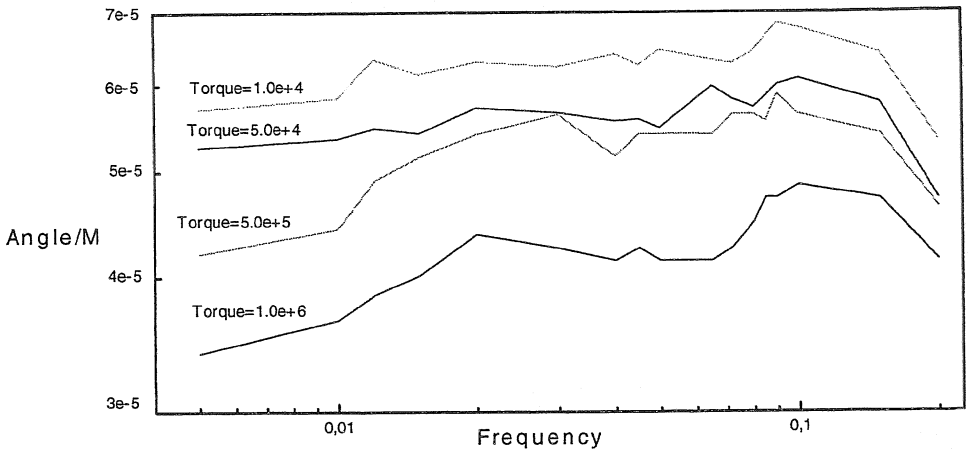
EZ4


6e-5
5e-5
4e-5
3e-5
Angle/M
Torque=5e+4
Torque=5e+5
Torque=1e+6
0,01
Frequence
0,1

EZ3


0,0001
0.00009
0.00008
0.00007
0.00006
0.00005
Angle/M
Torque=1.0e+4
Torque=5.0e+4
Torque=5.0e+5
Torque=1.0e+6
0,01
Frequency
0,1

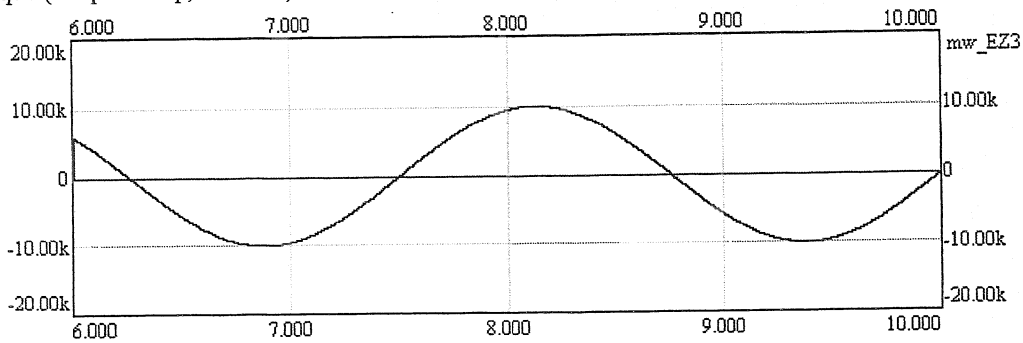
EZ4


7e-5
6e-5
5e-5
4e-5
3e-5
Angle/M
Torque=1.0e+4
Torque=5.0e+4
Torque=5.0e+5
Torque=1.0e+6
0,01
0,1
Frequency

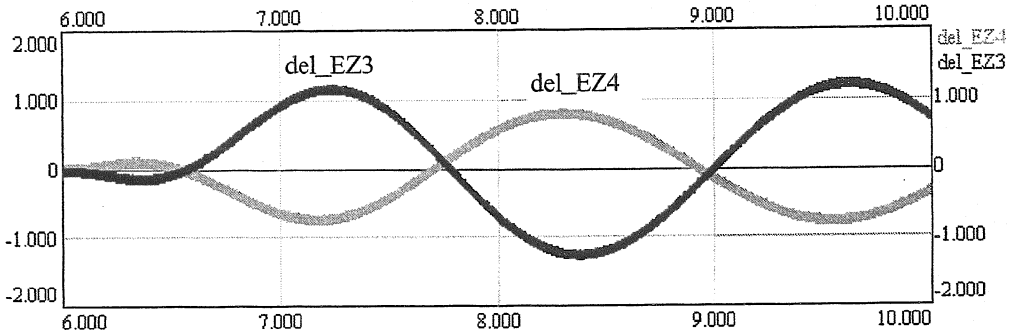
(2) Modified parameters

(a) Rkq*2

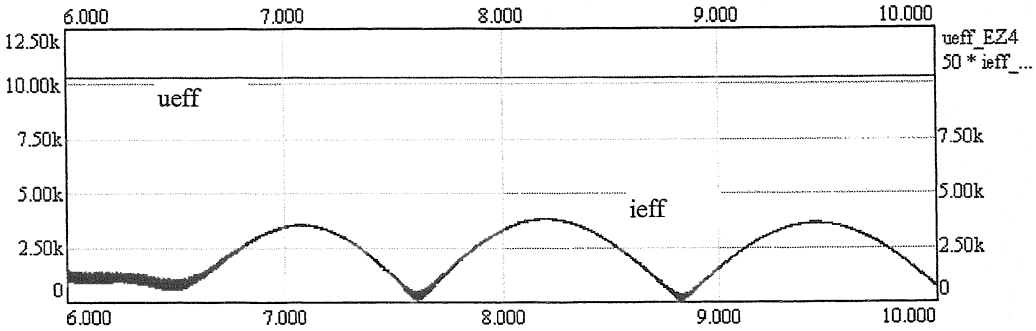
Torque (Rkq=2*Rkq , f=0.1Hz)



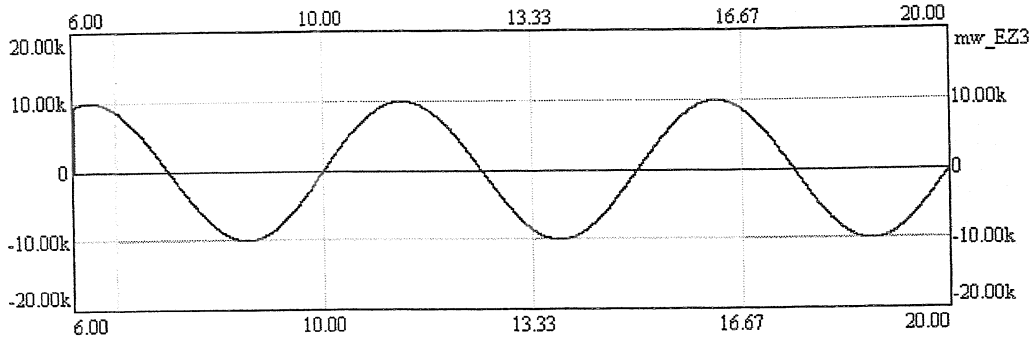
Angle (Rkq=2*Rkq , f=0.1Hz)



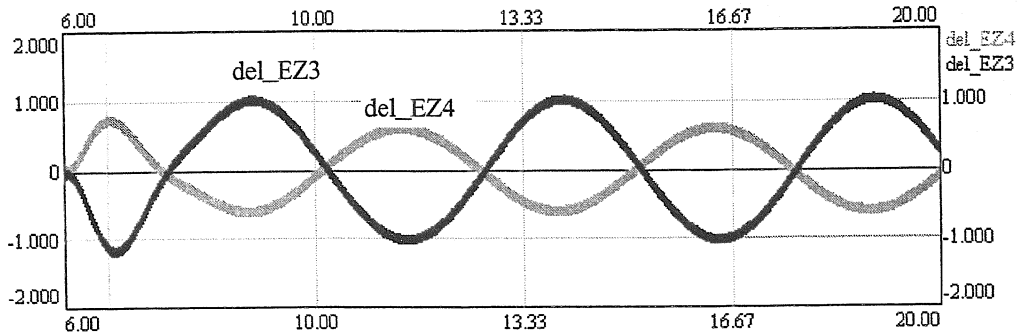
Voltage and current (Rkq=2*Rkq , f=0.1Hz)



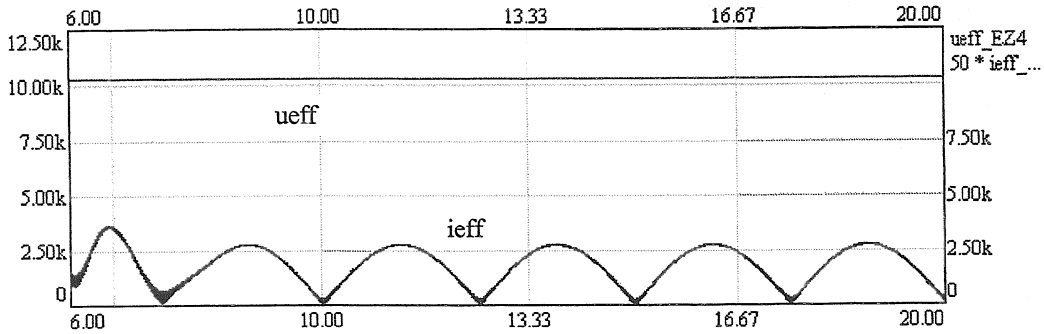
Torque(Rkq=2*Rkq , f=0.05Hz)



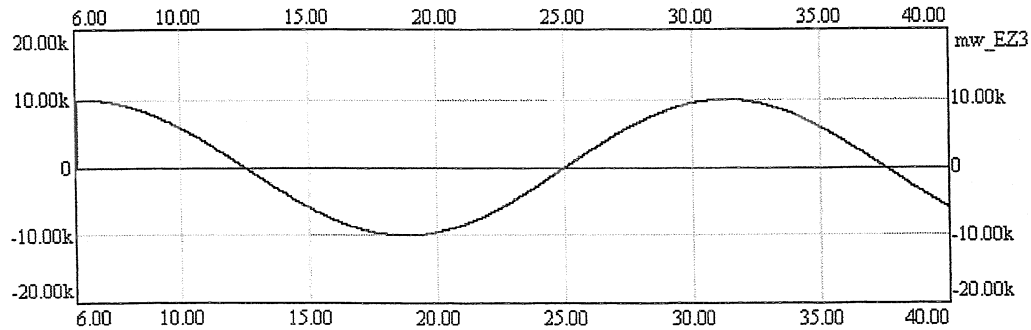
Angle (Rkq=2*Rkq , f=0.05Hz)



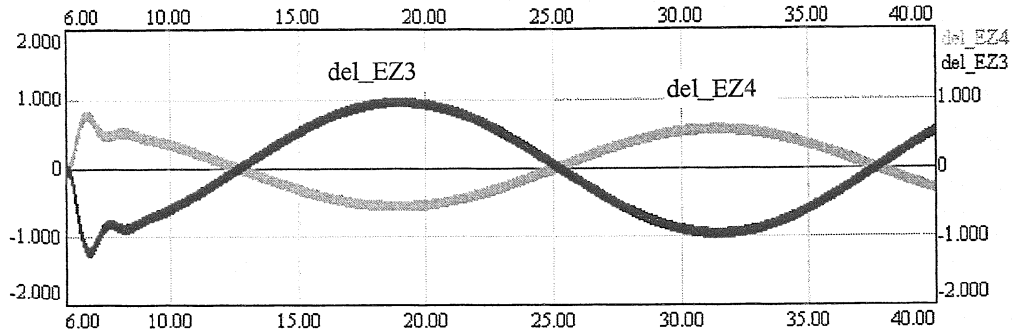
Voltage , current (Rkq=2*Rkq , f=0.05Hz)



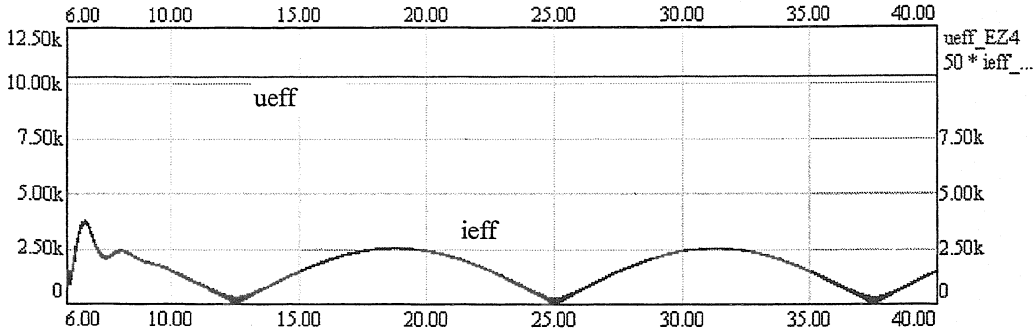
Torque (Rkq=2*Rkq , f=0.01Hz)



Angle (Rkq=2*Rkq , f=0.01Hz)

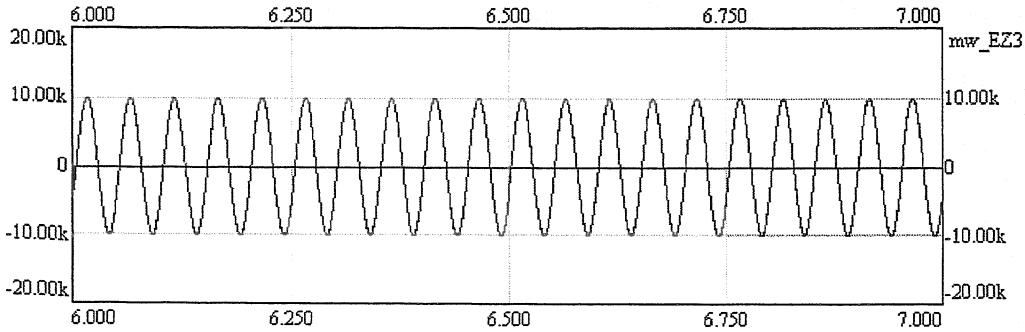


Voltage and current (Rkq=2*Rkq , f=0.01Hz)

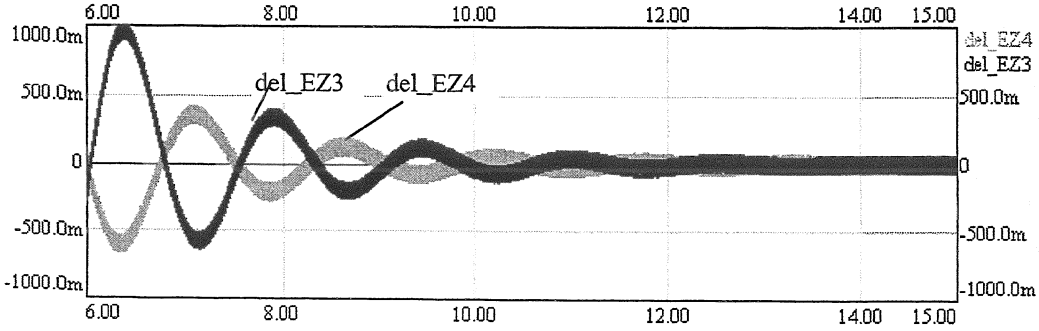


(b) Rkq=4*Rkq

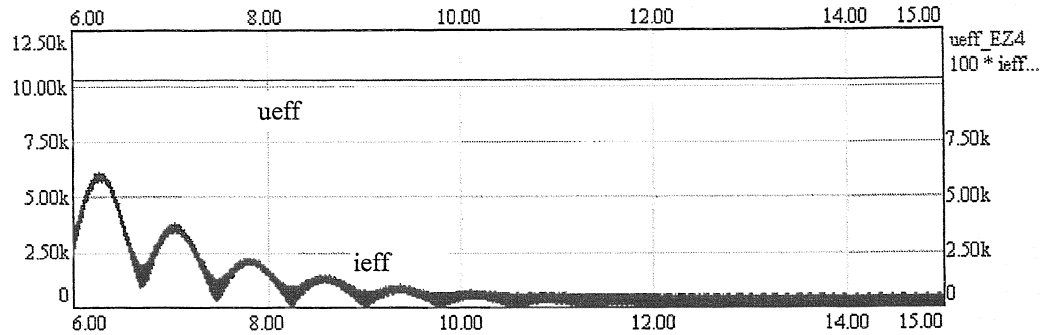
Torque (Rkq=4*Rkq , f=5.0Hz)



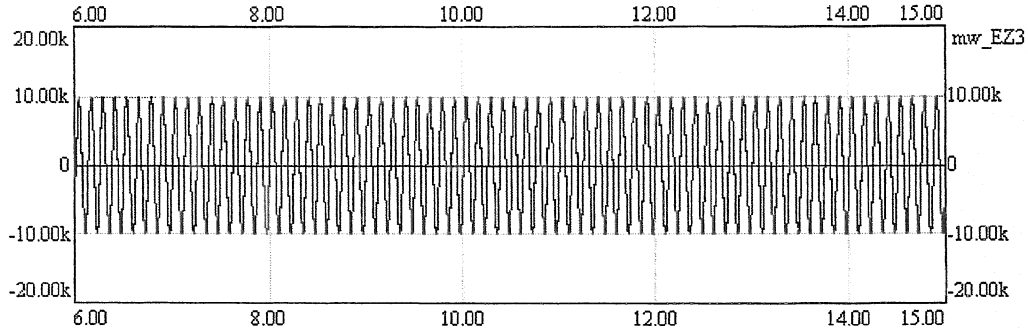
Angle (Rkq=4*Rkq , f=5.0Hz)



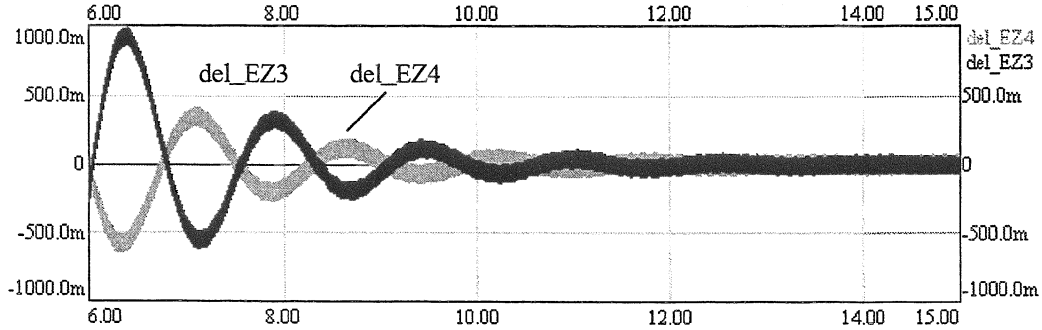
Voltage and current (Rkq=4*Rkq , f=5.0Hz)



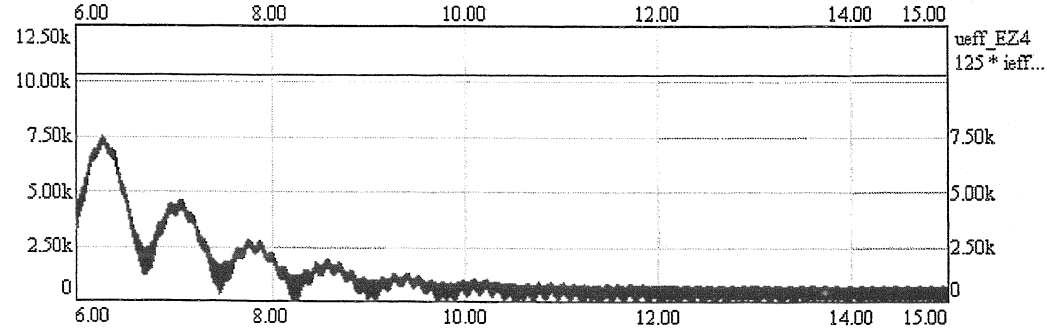
Torque (Rkq=4*Rkq , f=2.0Hz)



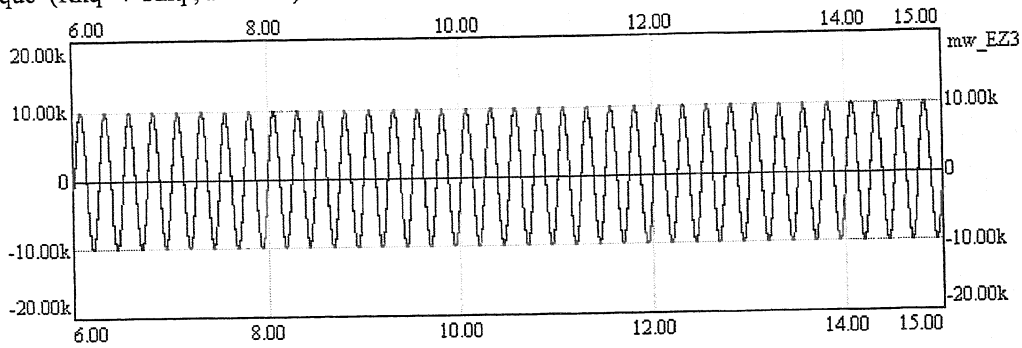
Angle (Rkq=4*Rkq , f=2.0Hz)



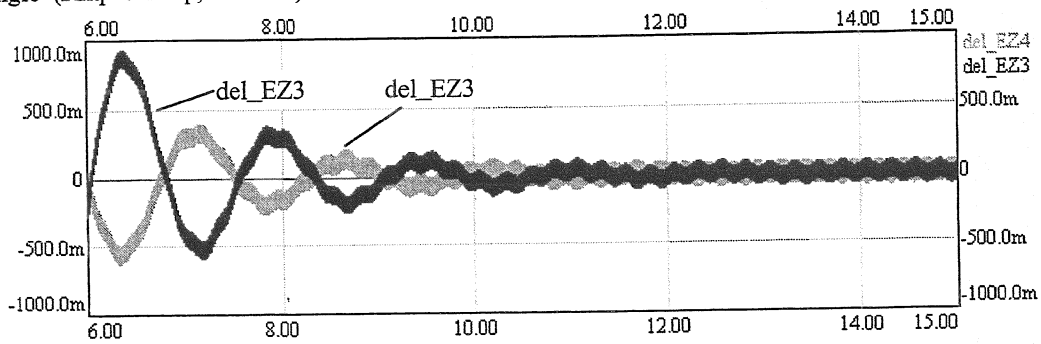
Voltage and current (Rkq=4*Rkq , f=2.0Hz)



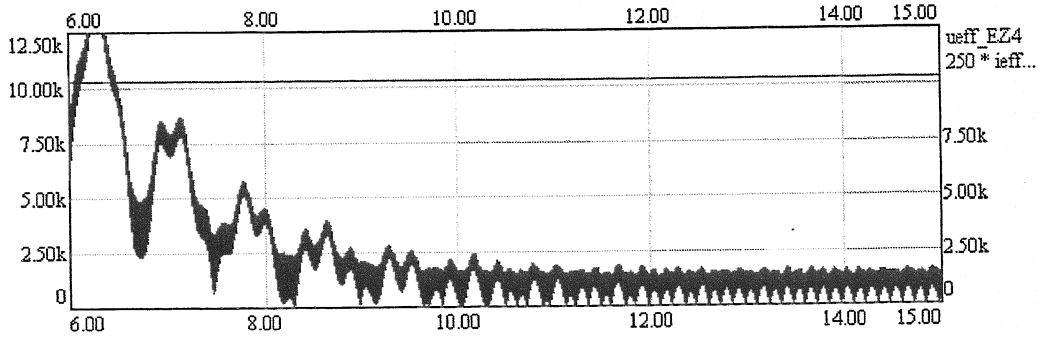
Torque (Rkq=4*Rkq , f=1.0Hz)



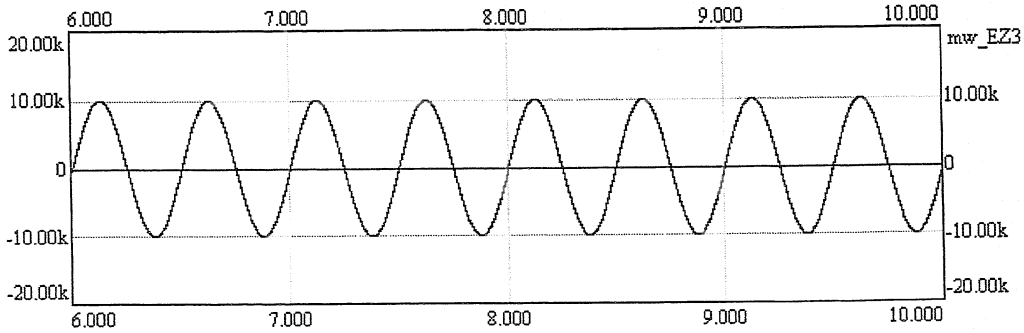
Angle (Rkq=4*Rkq , f=1.0Hz)



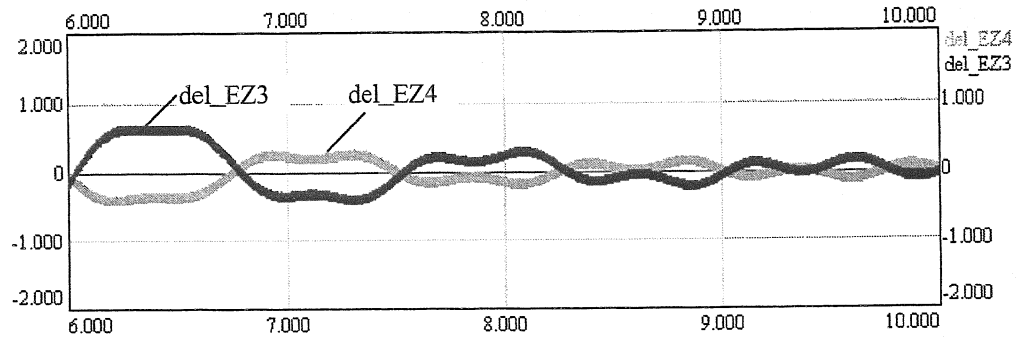
Voltage and current (Rkq=4*Rkq , f=1.0Hz)



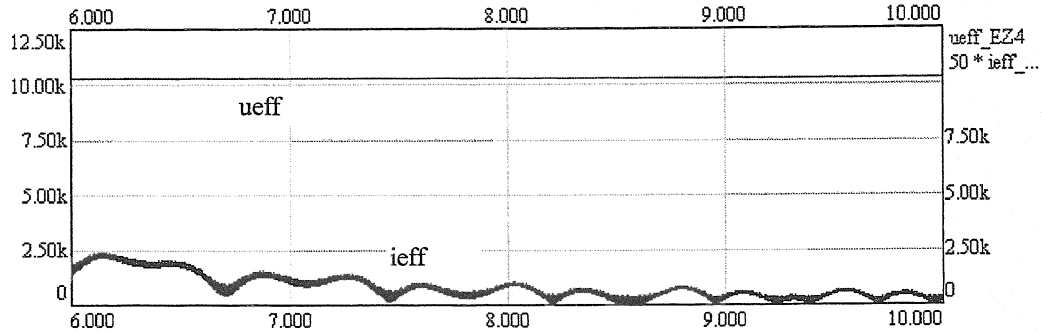
Torque (Rkq=4*Rkq , f=0.5Hz)



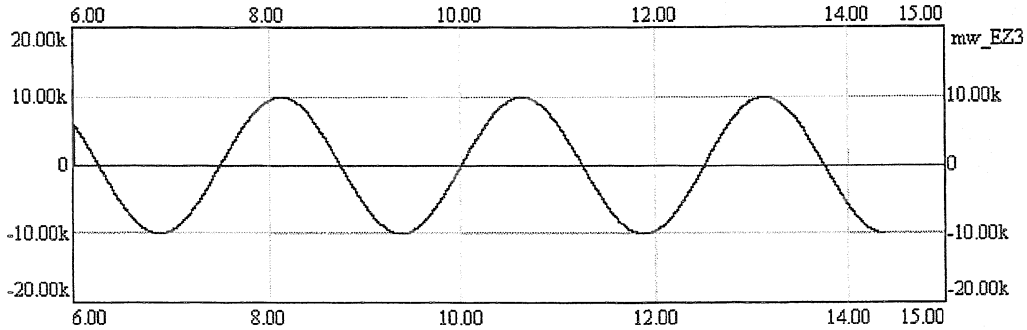
Angle (Rkq=4*Rkq , f=0.5Hz)



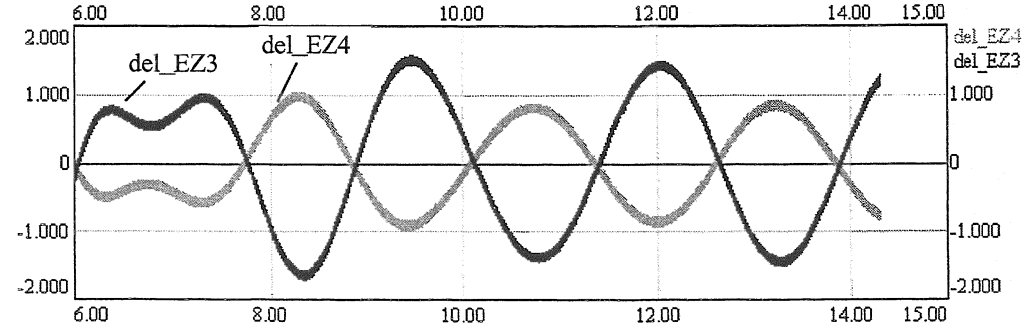
Voltage and current (Rkq=4*Rkq , f=0.5Hz)



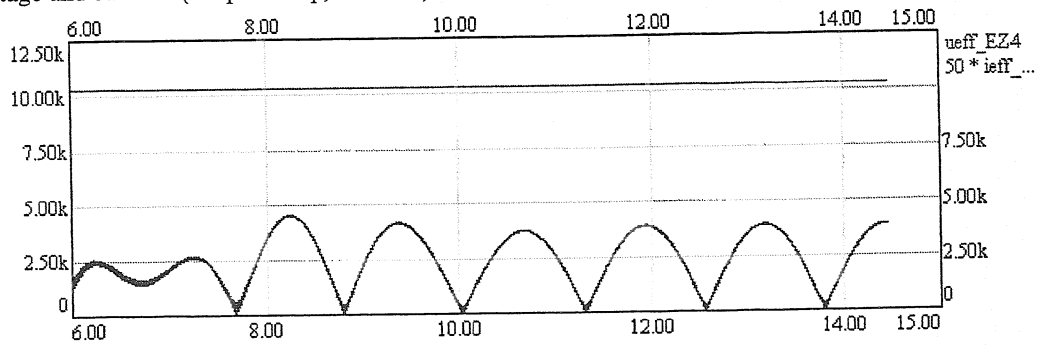
Torque (Rkq=4*Rkq , f=0.1Hz)



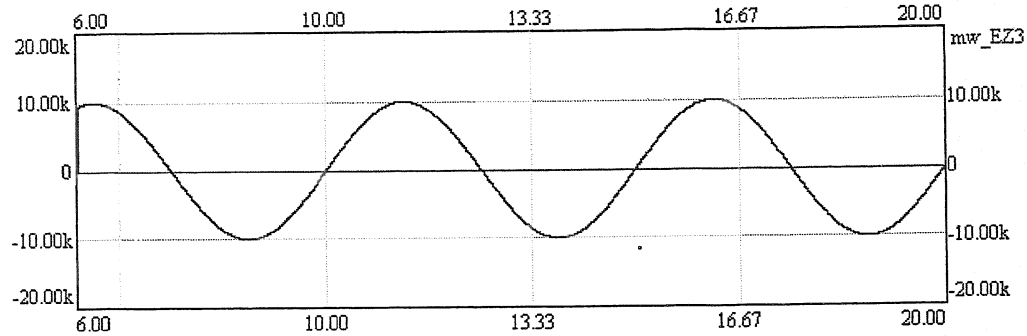
Angle (Rkq=4*Rkq , f=0.1Hz)



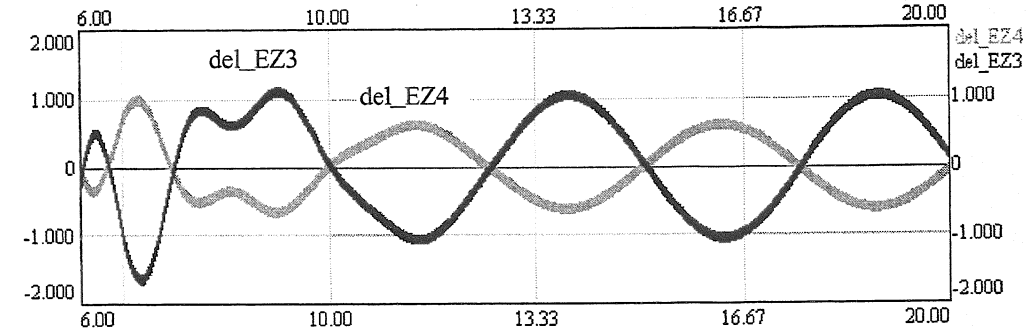
Voltage and current (Rkq=4*Rkq , f=0.1Hz)



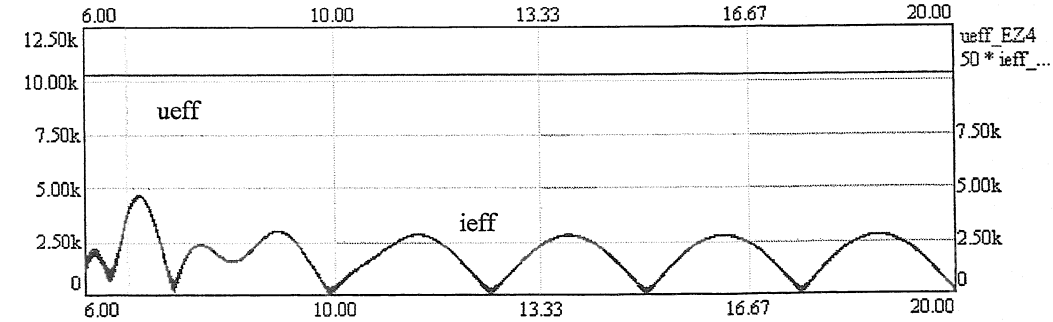
Torque (Rkq=4*Rkq , f=0.05Hz)



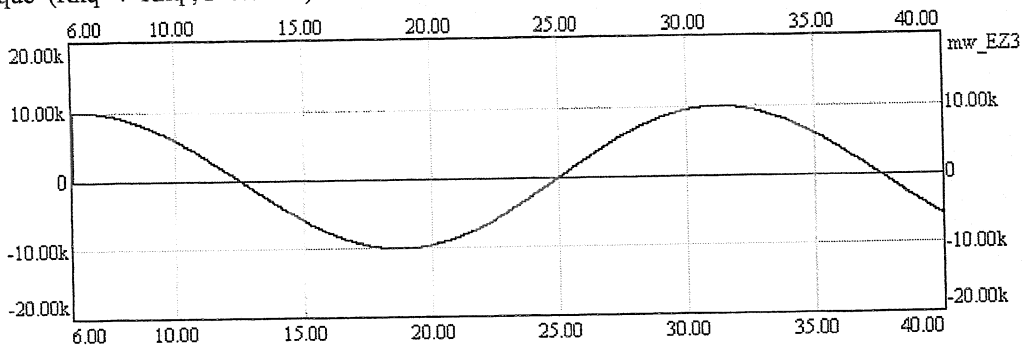
Angle (Rkq=4*Rkq , f=0.05Hz)



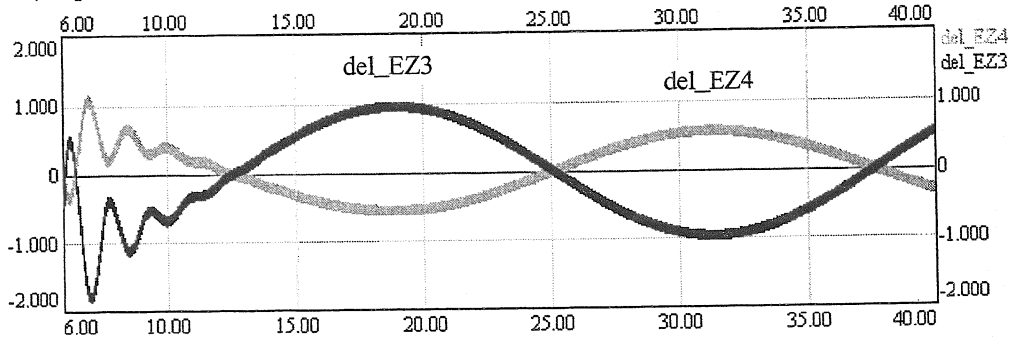
Voltage and current (Rkq=4*Rkq , f=0.05Hz)



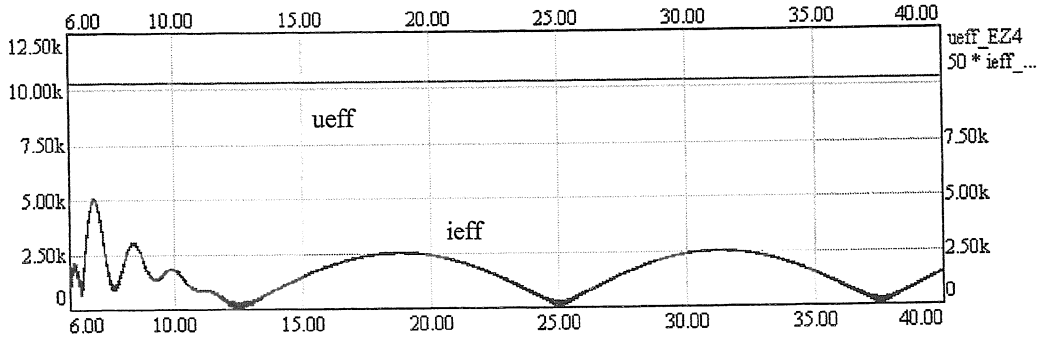
Torque (Rkq=4*Rkq , f=0.01Hz)



Angle (Rkq=4*Rkq , f=0.01Hz)

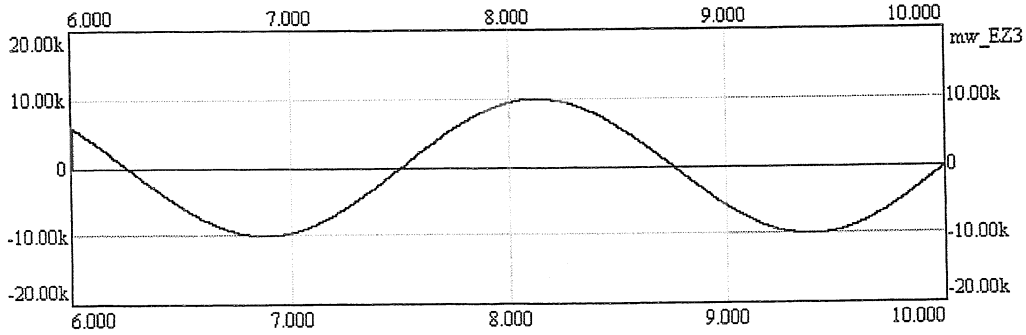


Voltage and current (Rkq=4*Rkq , f=0.01Hz)

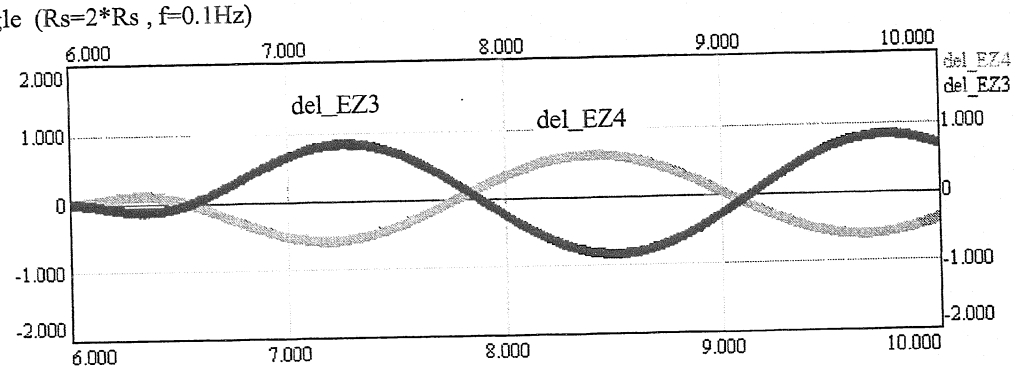


(c) Rs=Rs*2

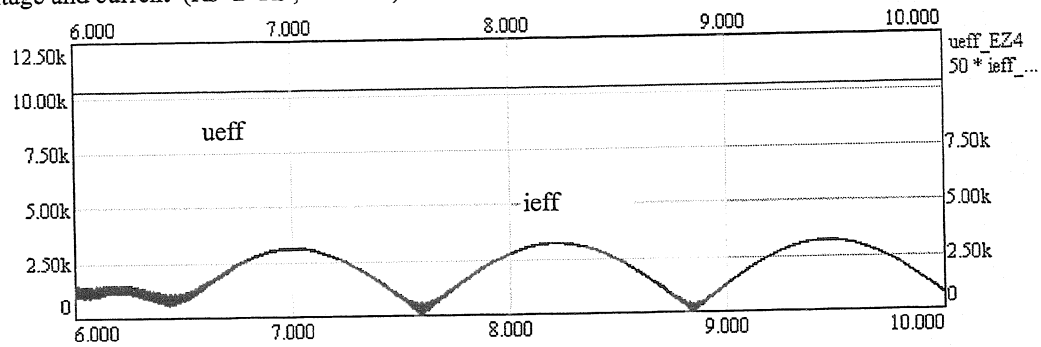
Torque (Rs=2*Rs , f=0.1Hz)



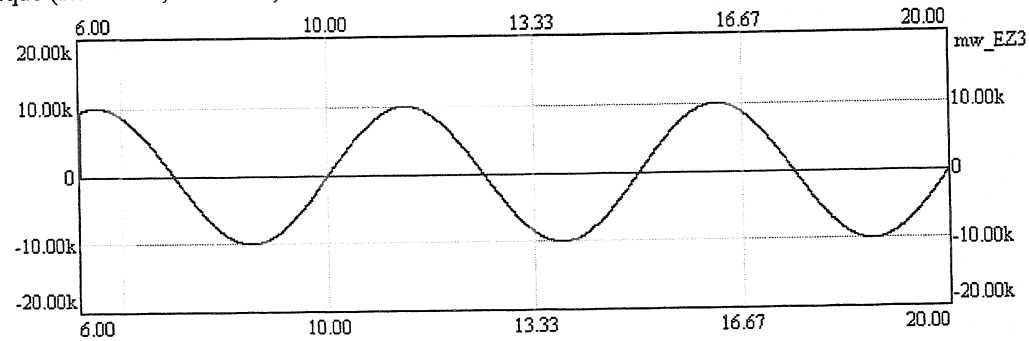
Angle (Rs=2*Rs , f=0.1Hz)



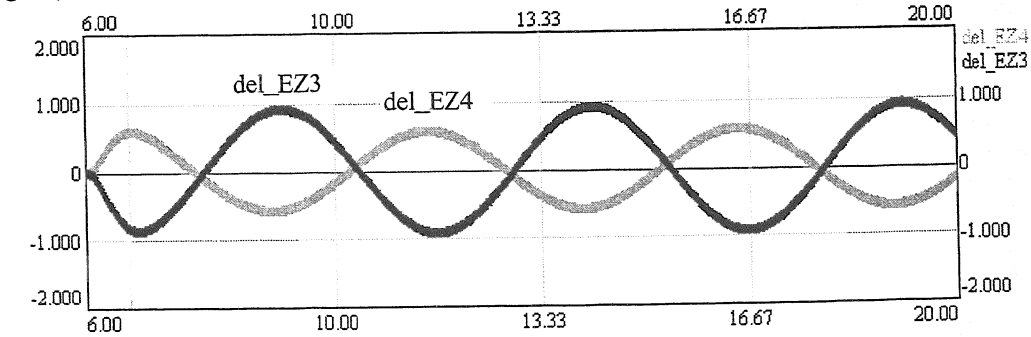
Voltage and current (Rs=2*Rs , f=0.1Hz)



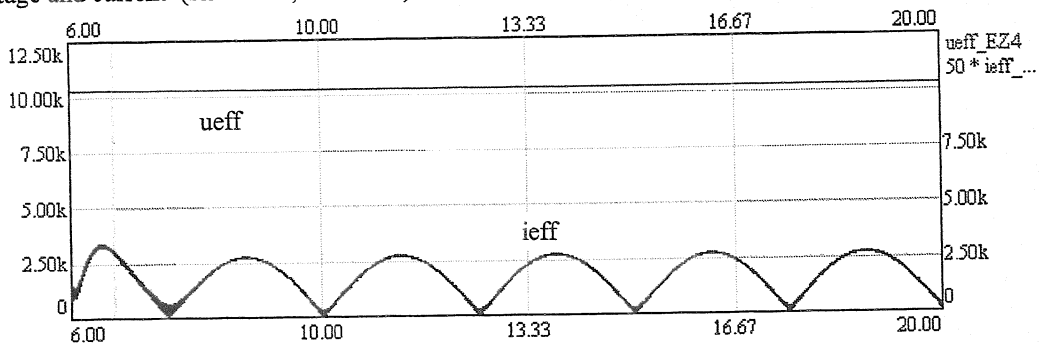
Torque (Rs=2*Rs , f=0.05Hz)



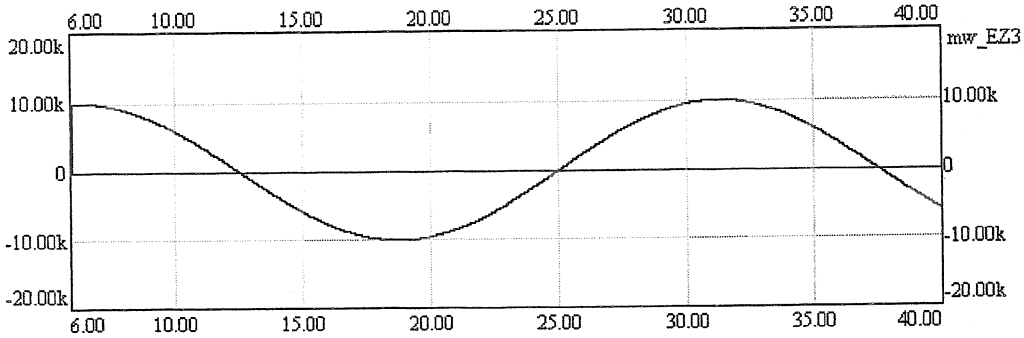
Angle (Rs=2*Rs , f=0.05Hz)



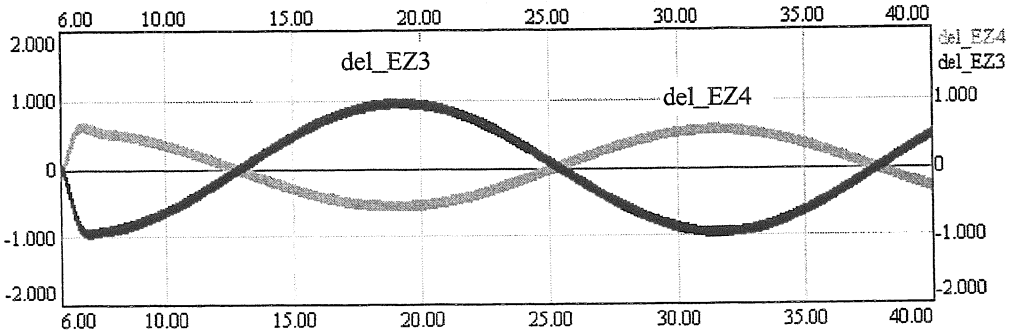
Voltage and current (Rs=2*Rs , f=0.05Hz)



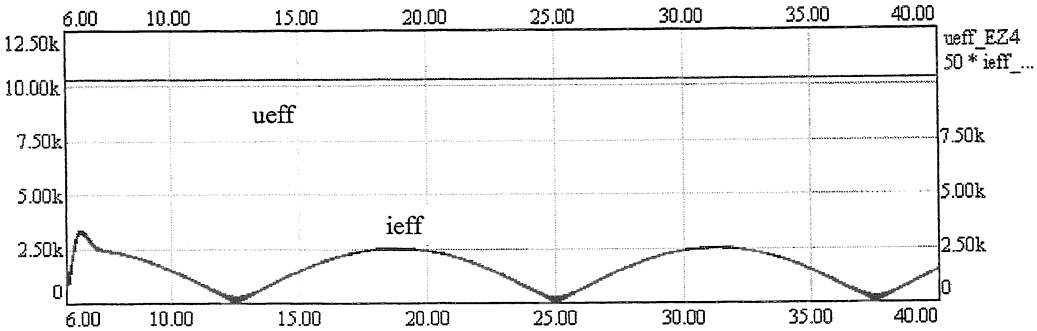
Torque (Rs=2*Rs , f=0.01Hz)



Angle (Rs=2*Rs , f=0.01Hz)

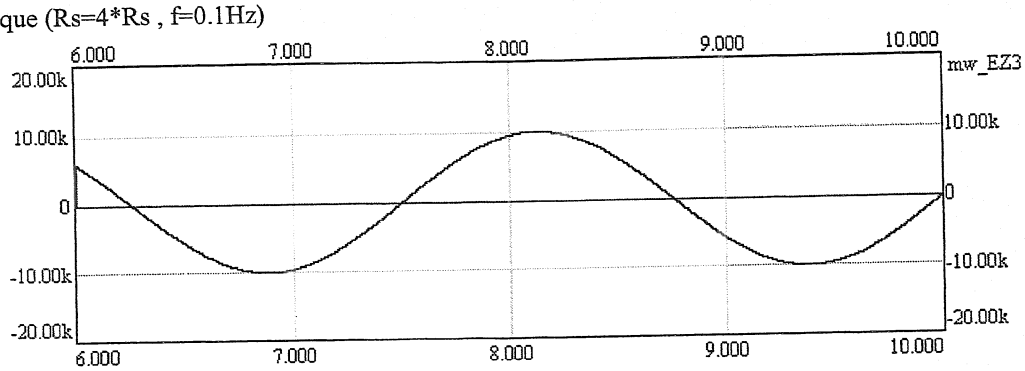


Voltage and current (Rs=2*Rs , f=0.01Hz)

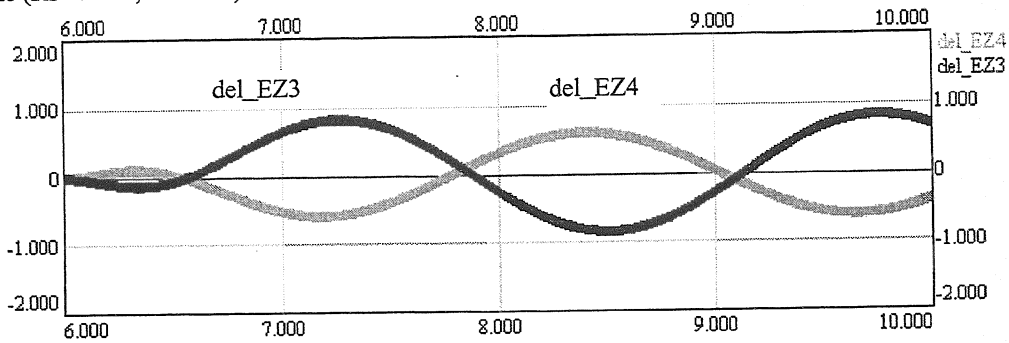


(d) Rs*4

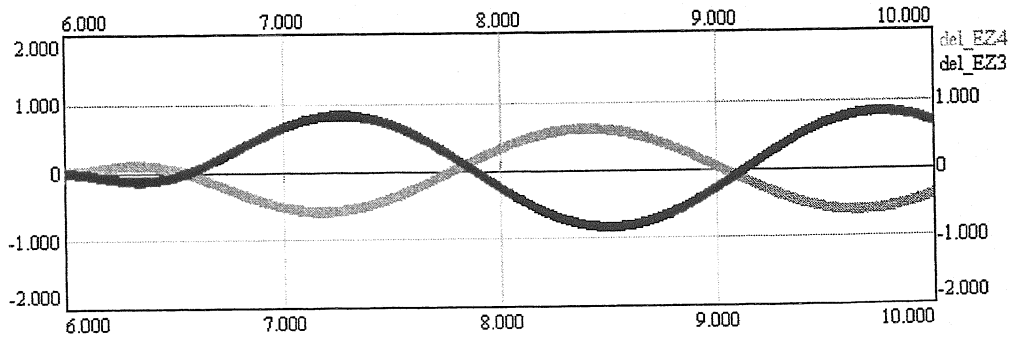
Torque (Rs=4*Rs , f=0.1Hz)



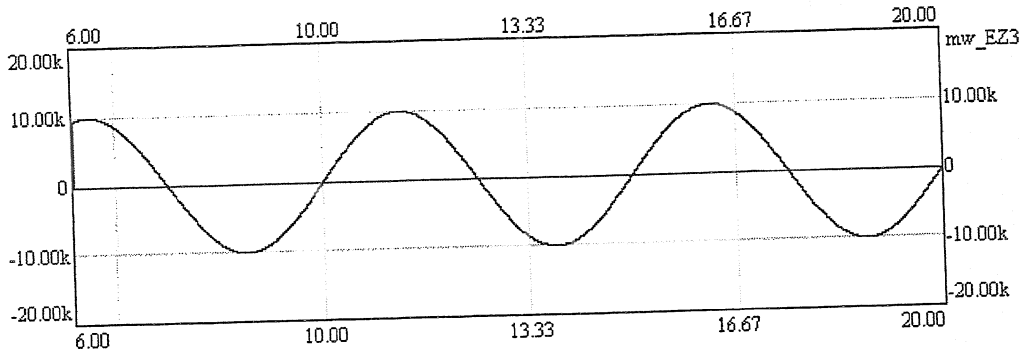
Angle (Rs=4*Rs , f=0.1Hz)



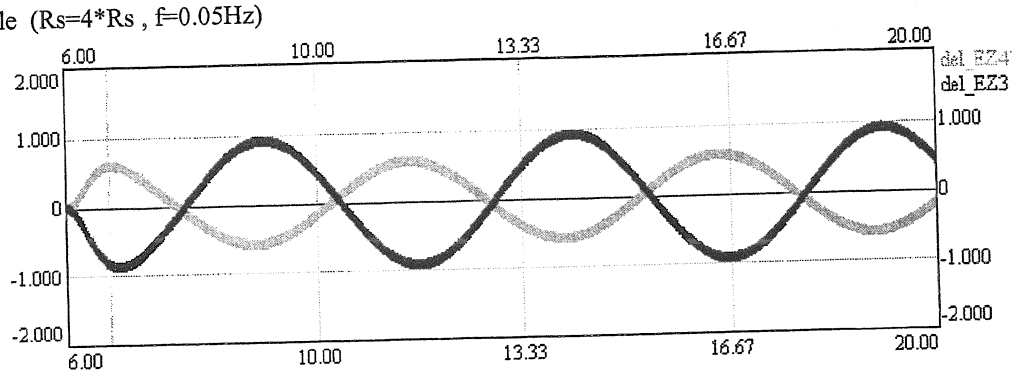
Voltage and current (Rs=4*Rs , f=0.1Hz)



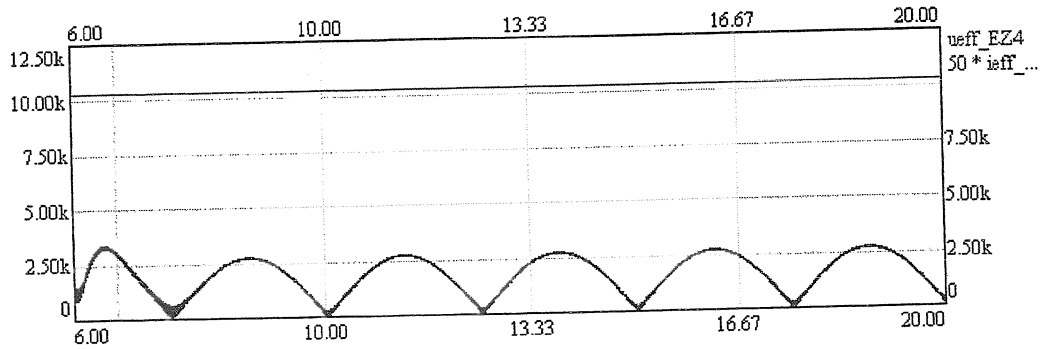
Torque (Rs=4*Rs , f=0.05Hz)



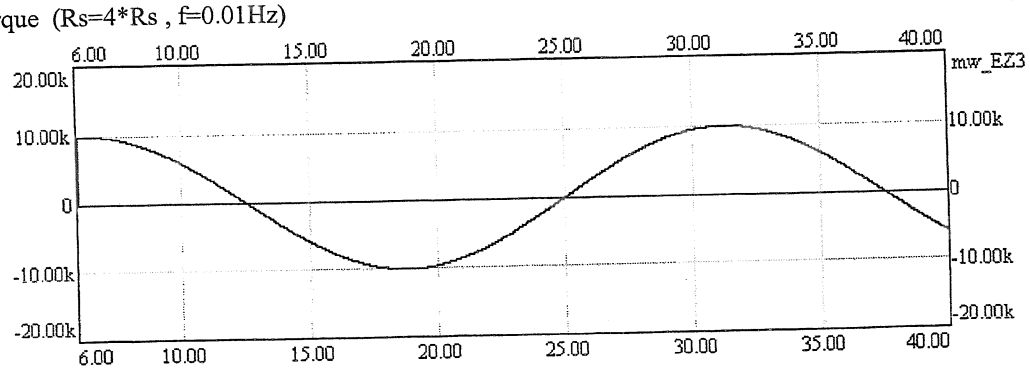
Angle (Rs=4*Rs , f=0.05Hz)



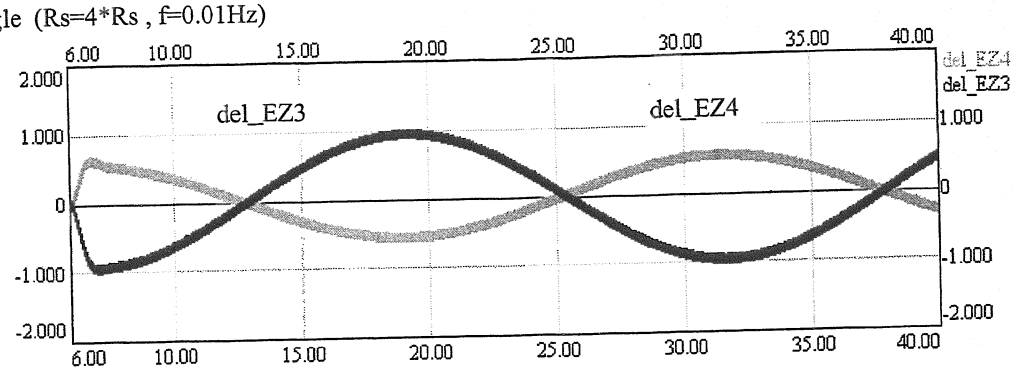
Voltage and current (Rs=4*Rs , f=0.05Hz)



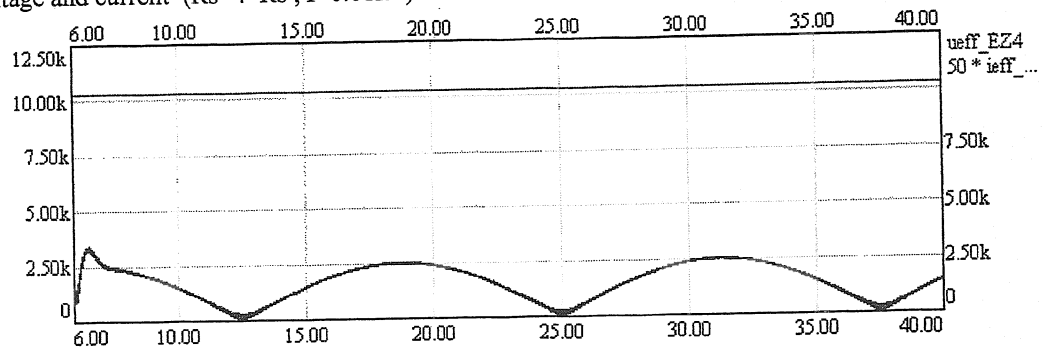
Torque (Rs=4*Rs , f=0.01Hz)



Angle (Rs=4*Rs , f=0.01Hz)

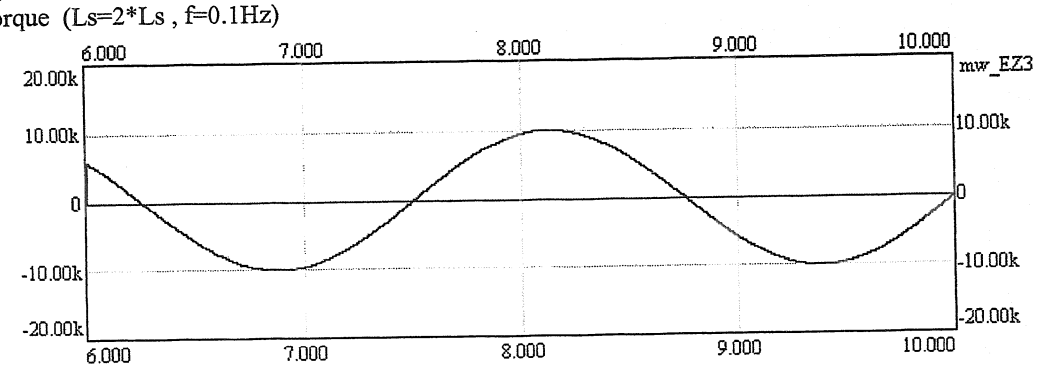


Voltage and current (Rs=4*Rs , f=0.01Hz)

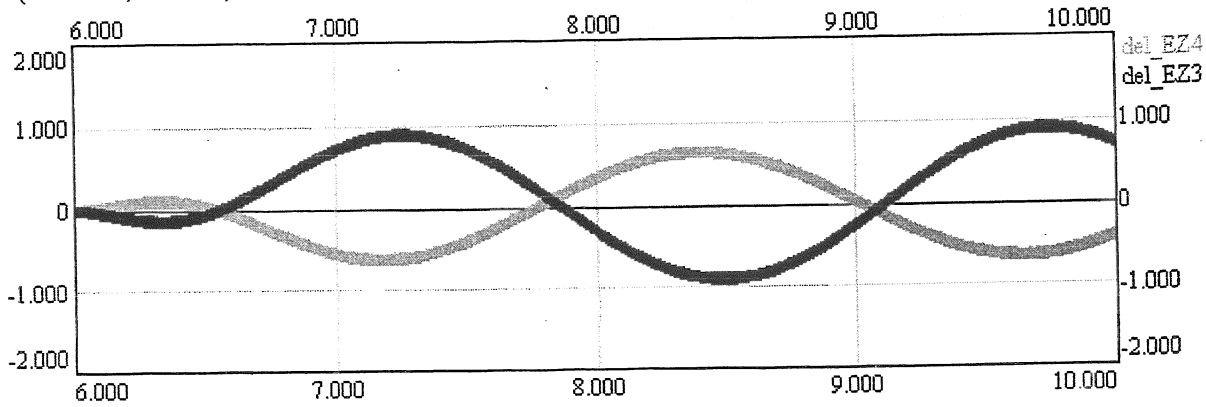


(e) Ls=2*Ls

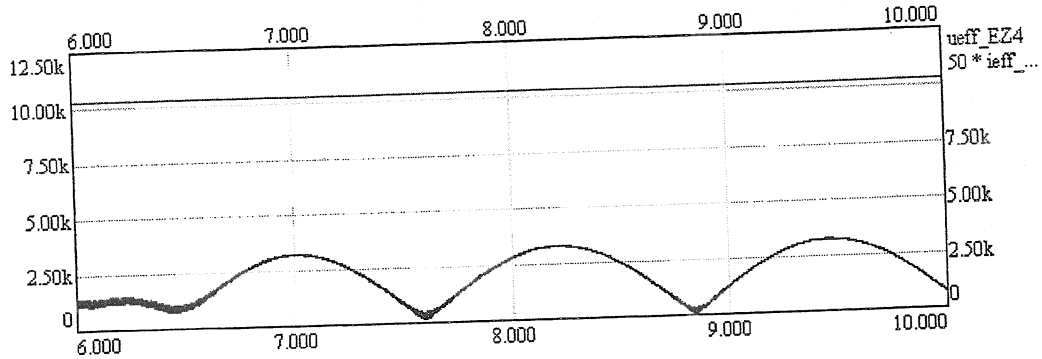
Torque (Ls=2*Ls , f=0.1Hz)



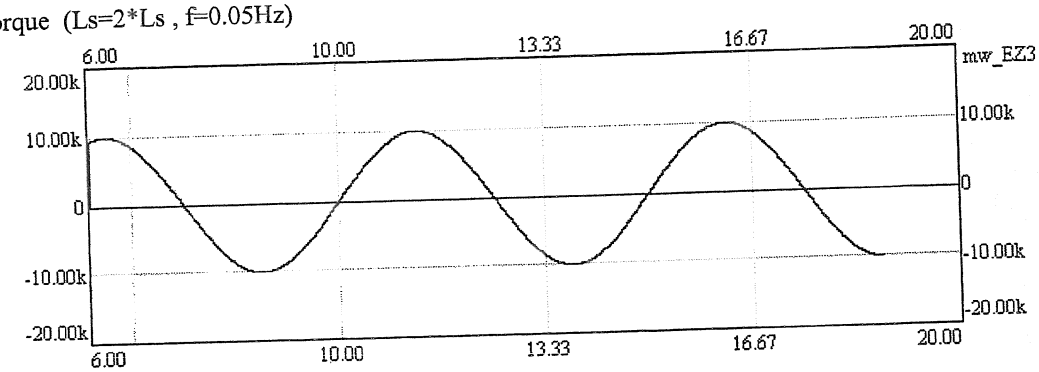
Angle (Ls=2*Ls , f=0.1Hz)



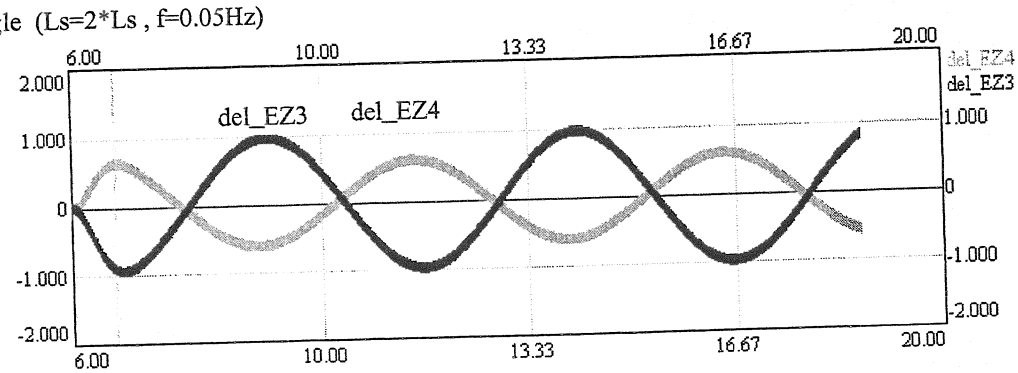
Voltage and current (Ls=2*Ls , f=0.1Hz)



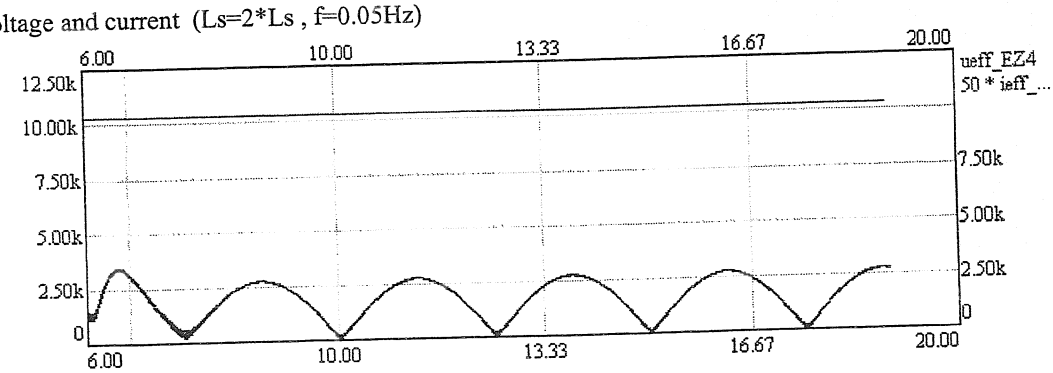
Torque (Ls=2*Ls , f=0.05Hz)



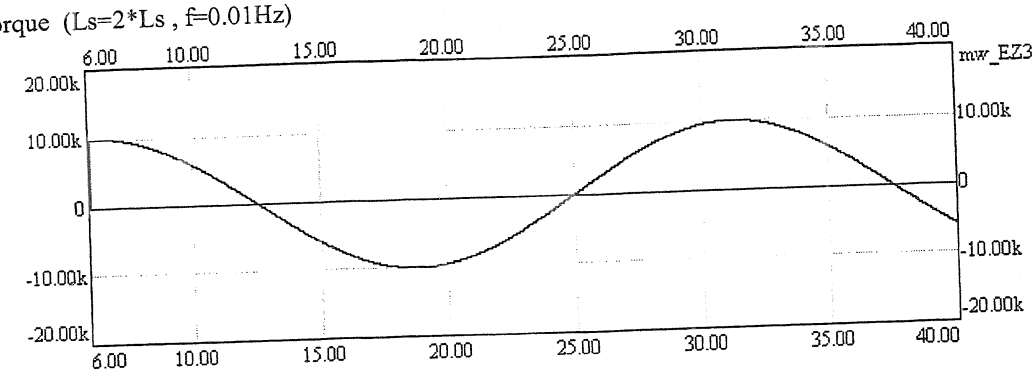
Angle (Ls=2*Ls , f=0.05Hz)



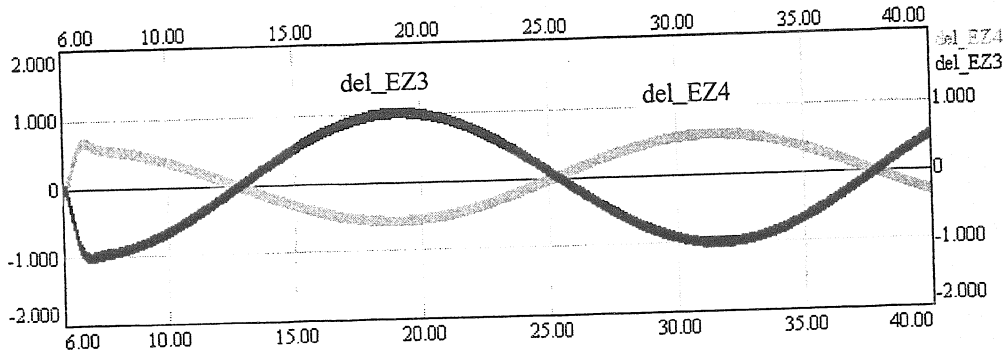
Voltage and current (Ls=2*Ls , f=0.05Hz)



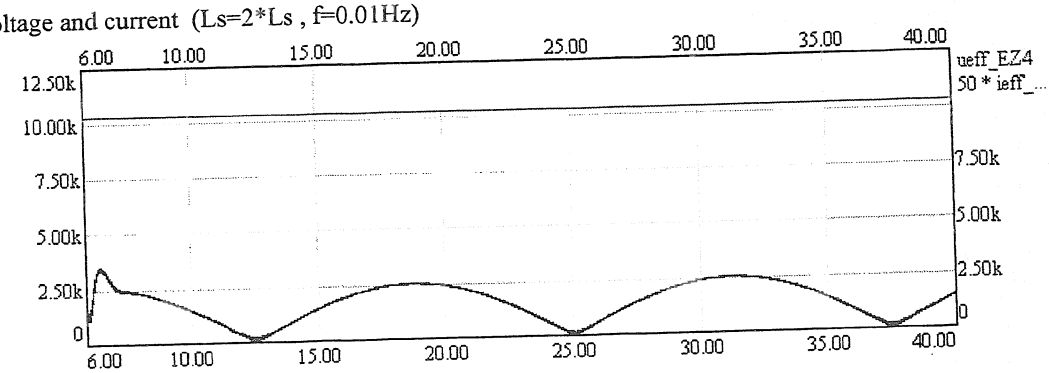
Torque (Ls=2*Ls , f=0.01Hz)



Angle (Ls=2*Ls , f=0.01Hz)

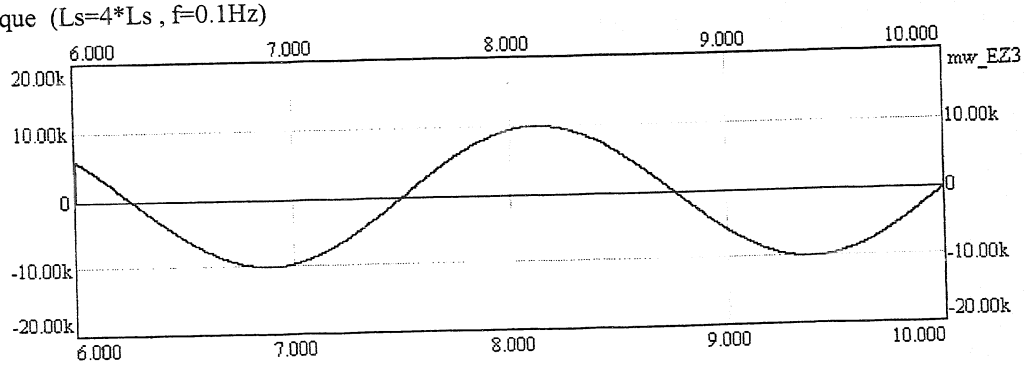


Voltage and current (Ls=2*Ls , f=0.01Hz)

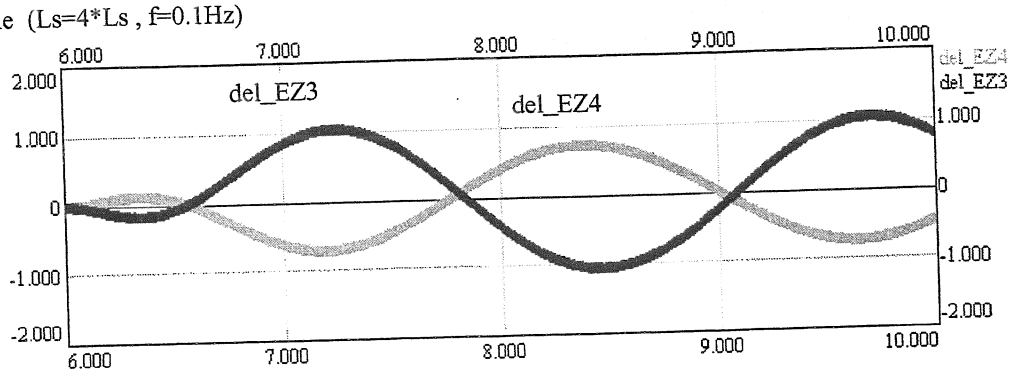


(f) Ls*4

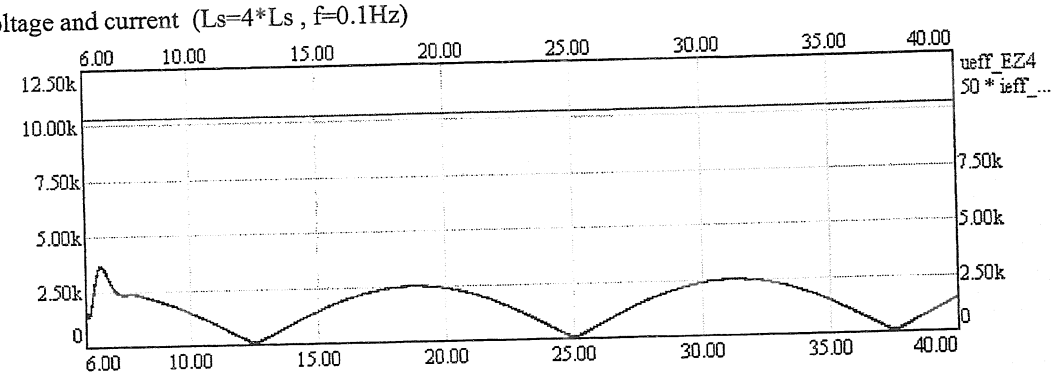
Torque (Ls=4*Ls , f=0.1Hz)



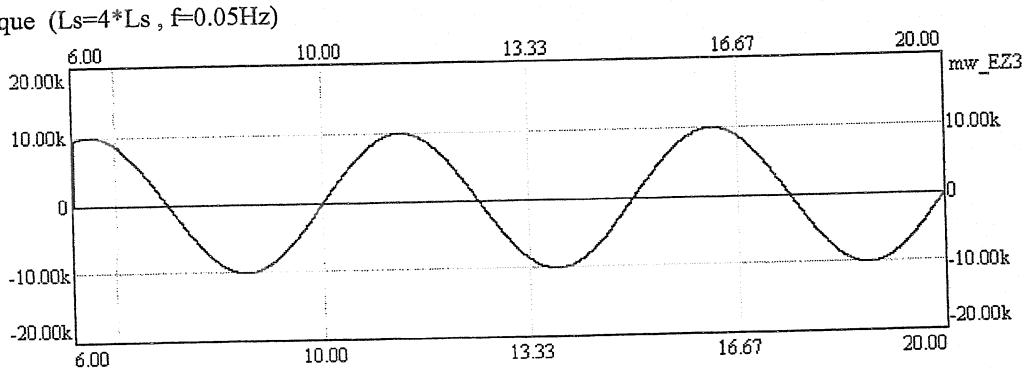
Angle (Ls=4*Ls , f=0.1Hz)



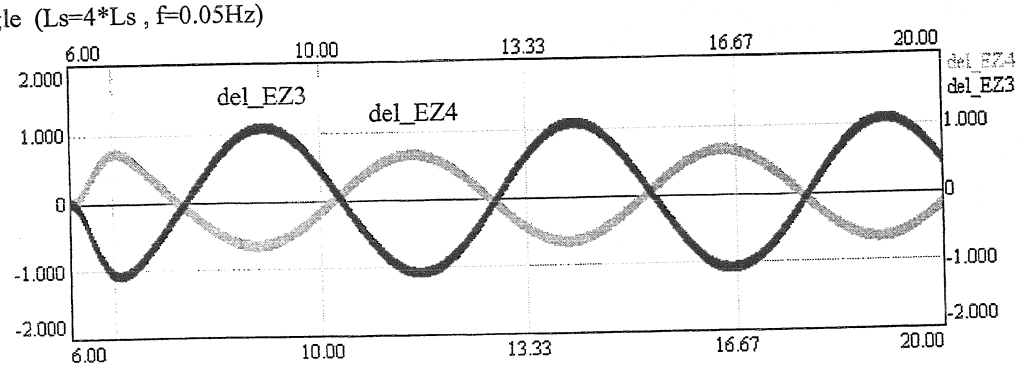
Voltage and current (Ls=4*Ls , f=0.1Hz)



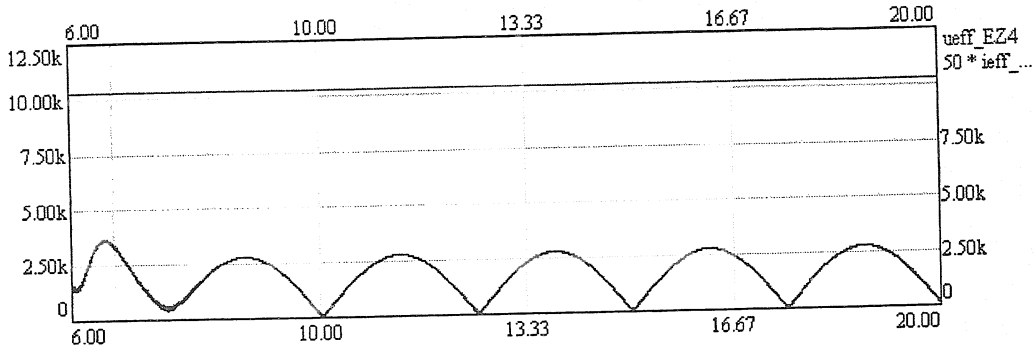
Torque (Ls=4*Ls , f=0.05Hz)



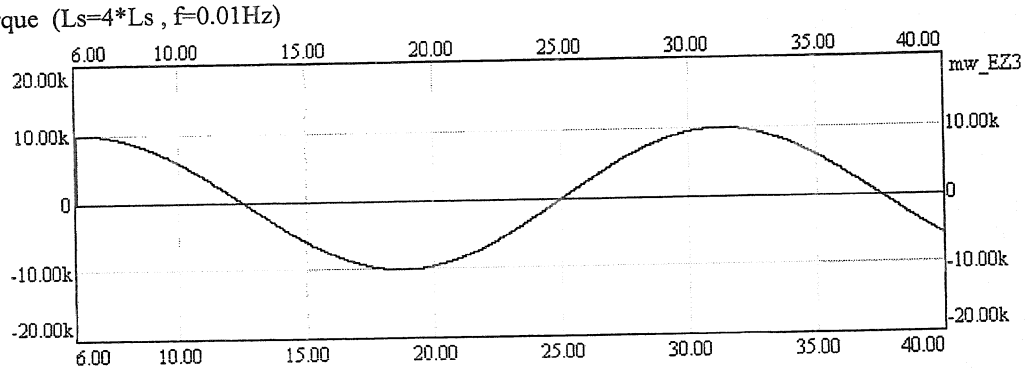
Angle (Ls=4*Ls , f=0.05Hz)



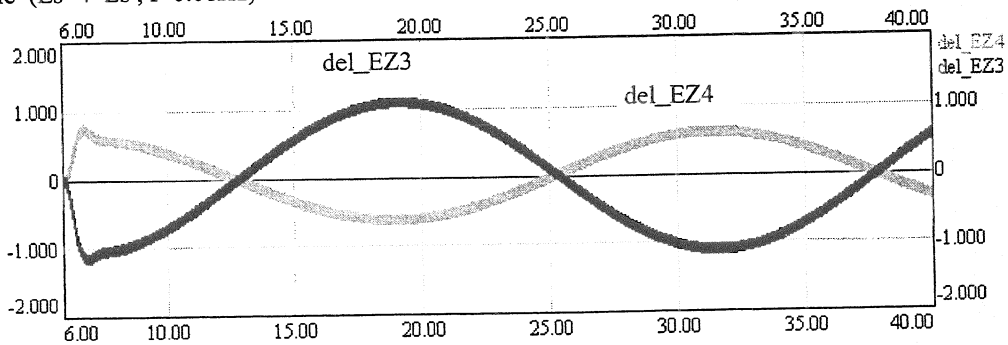
Voltage and current (Ls=4*Ls , f=0.05Hz)



Torque (Ls=4*Ls , f=0.01Hz)



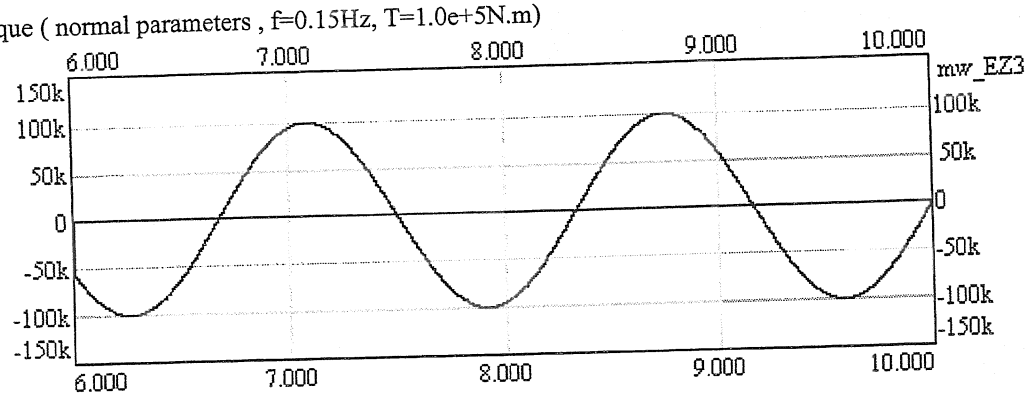
Angle (Ls=4*Ls , f=0.01Hz)



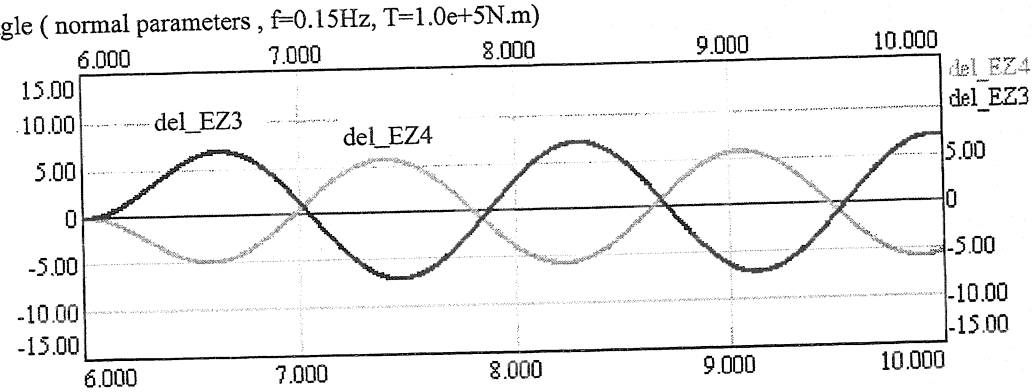
(3) Worst parameter of the generators (torque applied T=1.0e+5N.m at EZ3)

a. Use of normal generator parameters

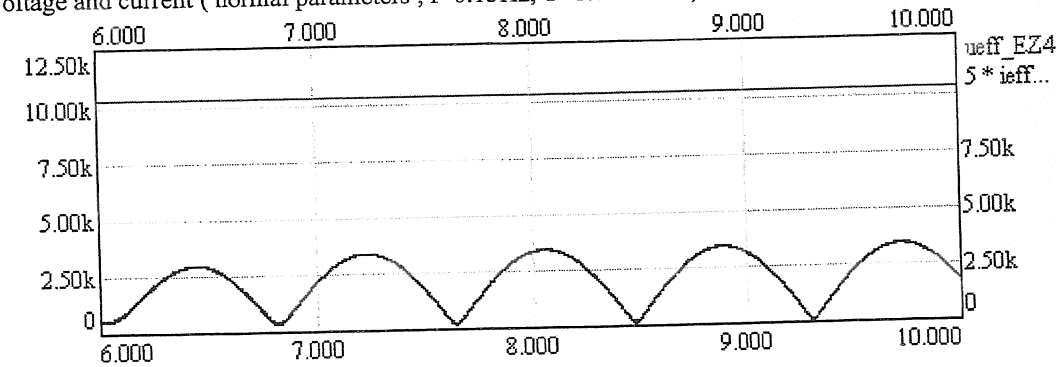
Torque (normal parameters , f=0.15Hz, T=1.0e+5N.m)



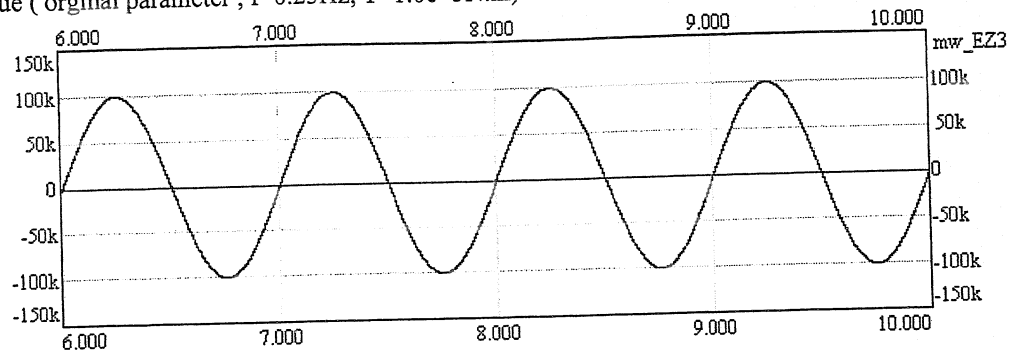
Angle (normal parameters , f=0.15Hz, T=1.0e+5N.m)



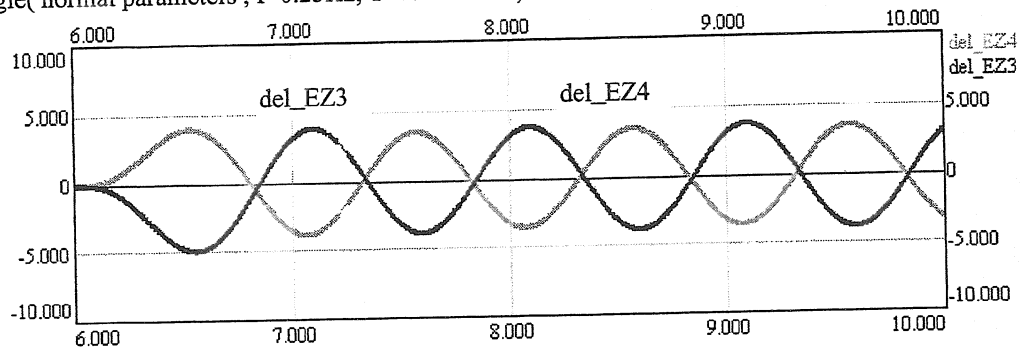
Voltage and current (normal parameters , f=0.15Hz, T=1.0e+5N.m)



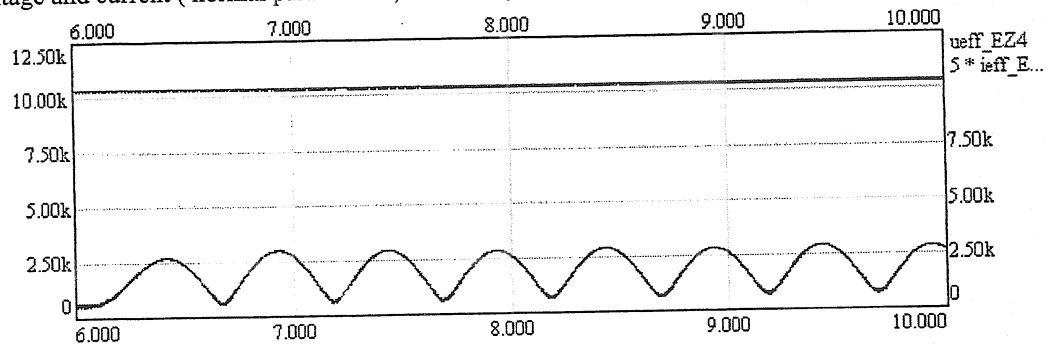
Torque (orginal parameter , f=0.25Hz, T=1.0e+5N.m)



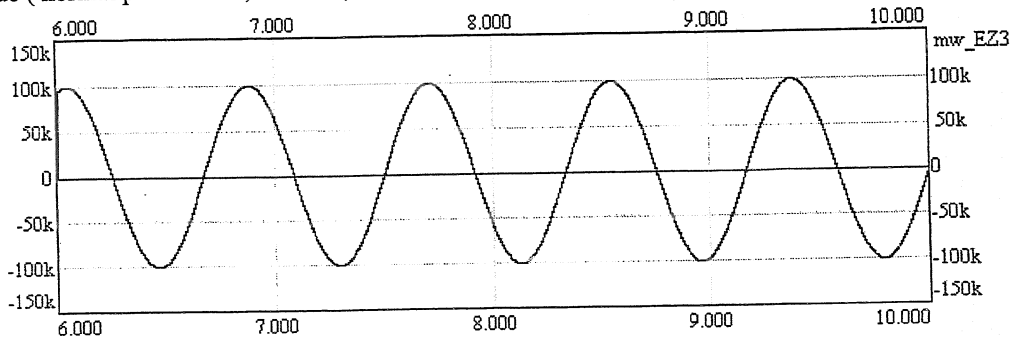
Angle(normal parameters , f=0.25Hz, T=1.0e+5N.m)



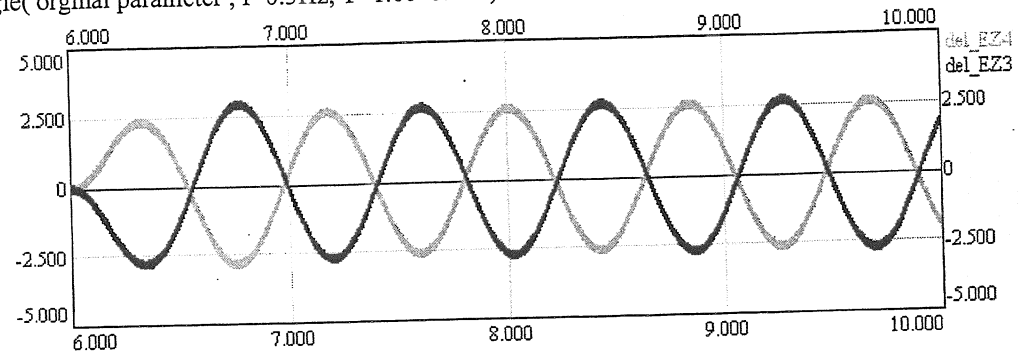
Voltage and current (normal parameters , f=0.25Hz, T=1.0e+5N.m)



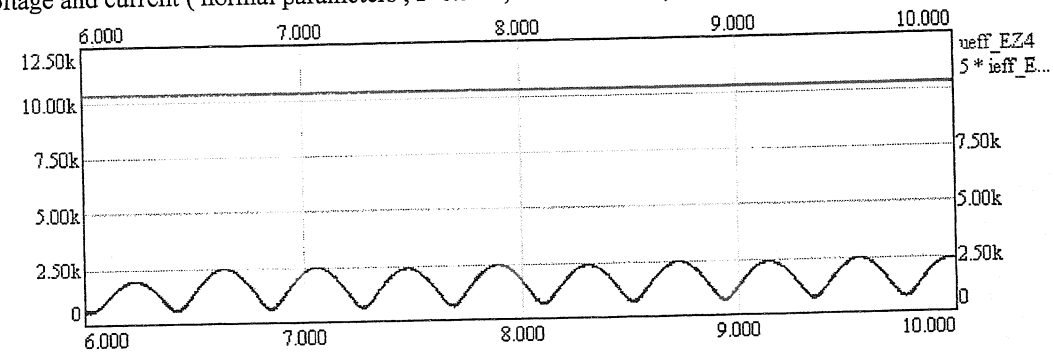
Torque (normal parameters , f=0.3Hz, T=1.0e+5N.m)



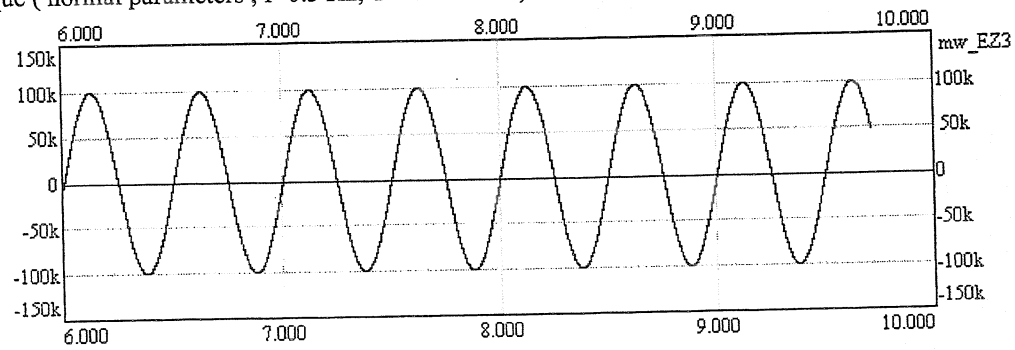
Angle(orginal parameter , f=0.3Hz, T=1.0e+5N.m)



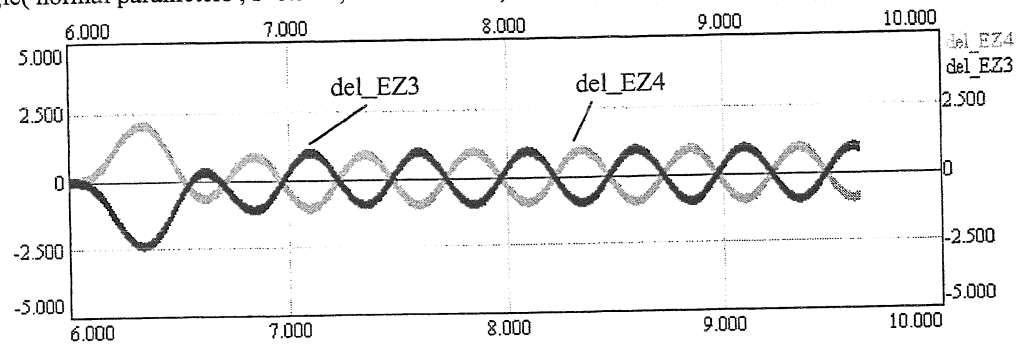
Voltage and current (normal parameters , f=0.3Hz, T=1.0e+5N.m)



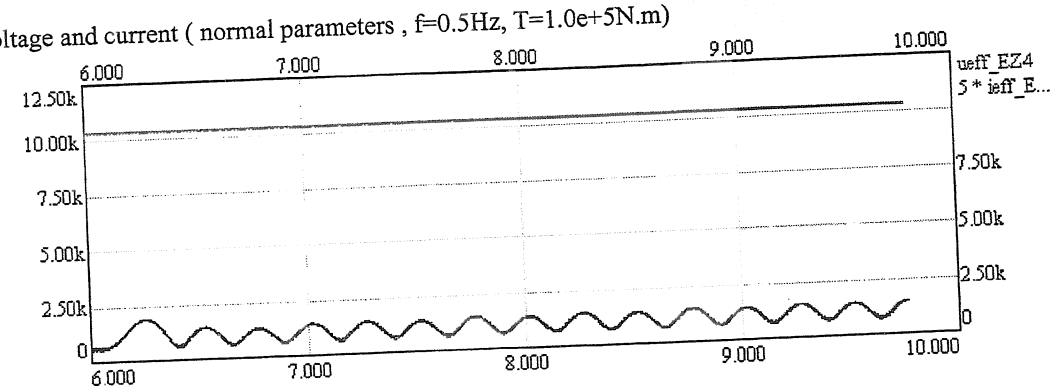
Torque (normal parameters , f=0.5 Hz, T=1.0e+5N.m)



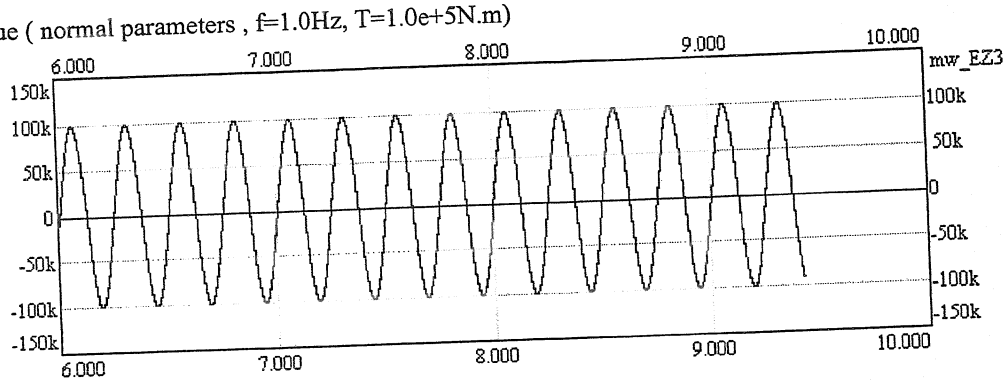
Angle(normal parameters , f=0.5Hz, T=1.0e+5N.m)



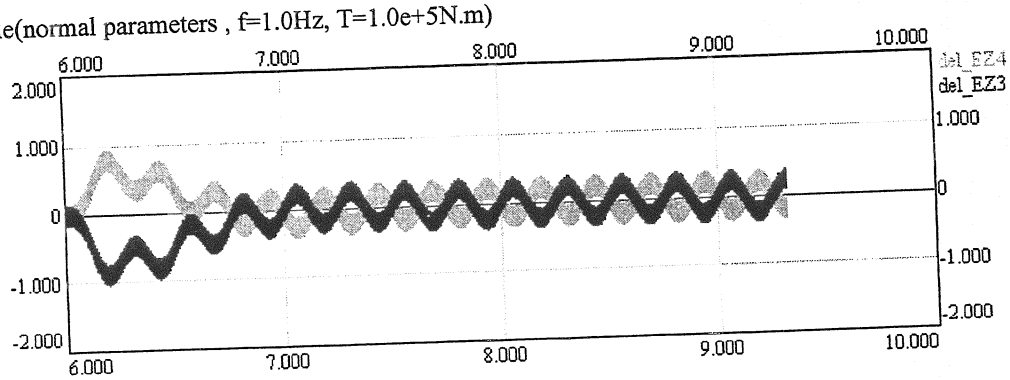
Voltage and current (normal parameters , f=0.5Hz, T=1.0e+5N.m)



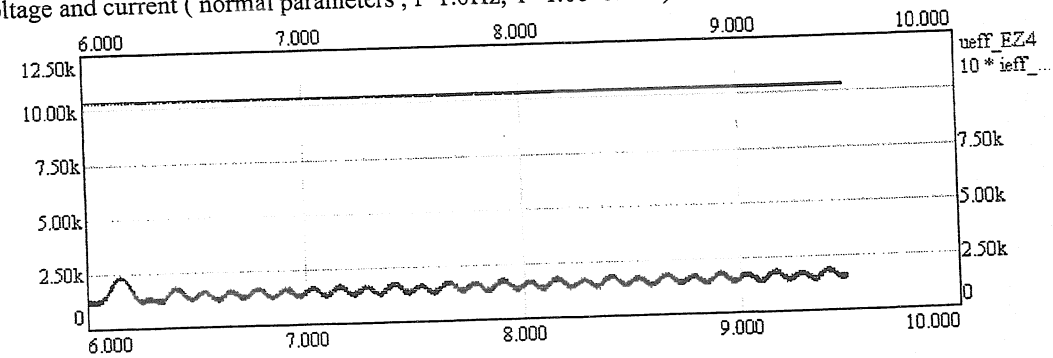
Torque (normal parameters , f=1.0Hz, T=1.0e+5N.m)



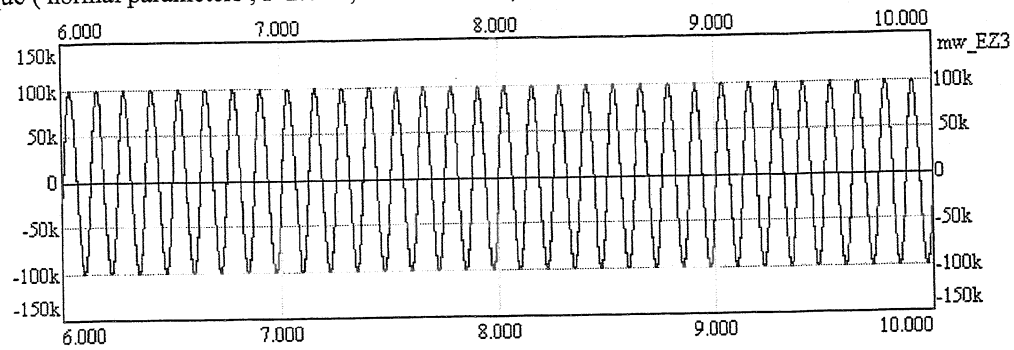
Angle(normal parameters , f=1.0Hz, T=1.0e+5N.m)



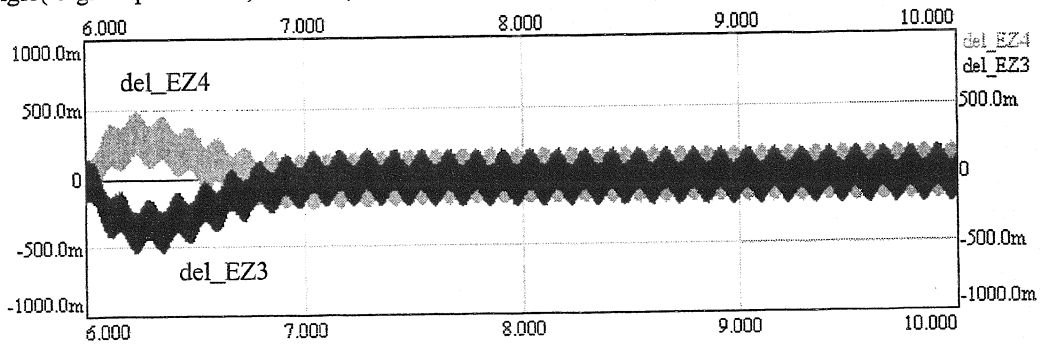
Voltage and current (normal parameters , f=1.0Hz, T=1.0e+5N.m)



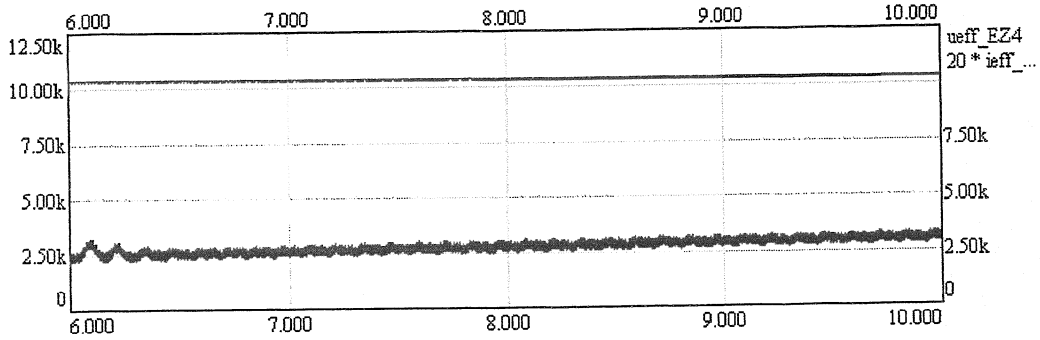
Torque (normal parameters , f=2.0Hz, T=1.0e+5N.m)



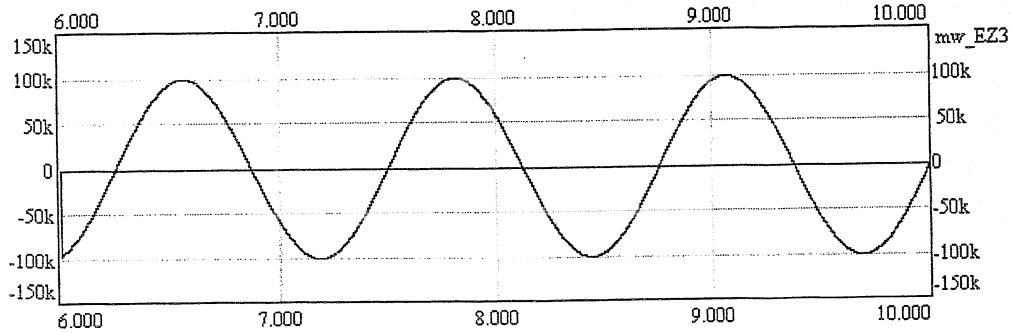
Angle(orginal parameter , f=2.0Hz, T=1.0e+5N.m)



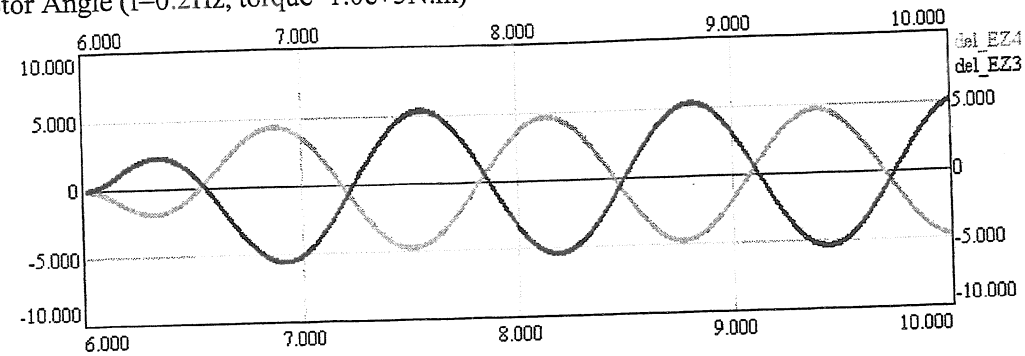
Voltage and current (orginal parameter , f=2.0Hz, T=1.0e+5N.m)



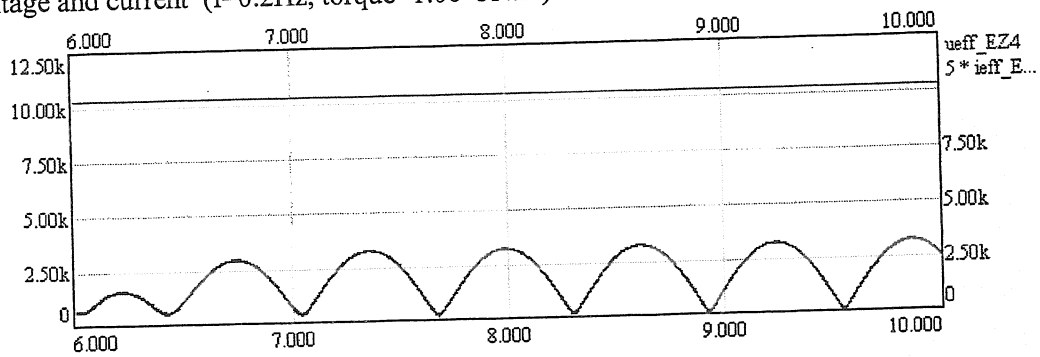
Torque (f=0.2Hz, torque=1.0e+5)



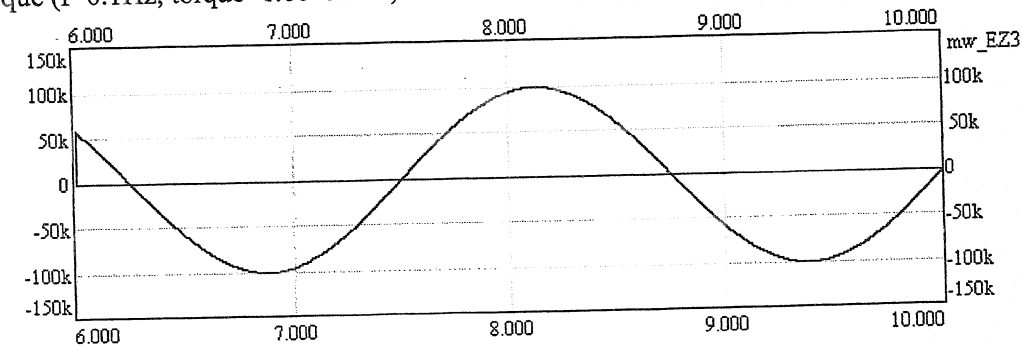
Rotor Angle (f=0.2Hz, torque=1.0e+5N.m)



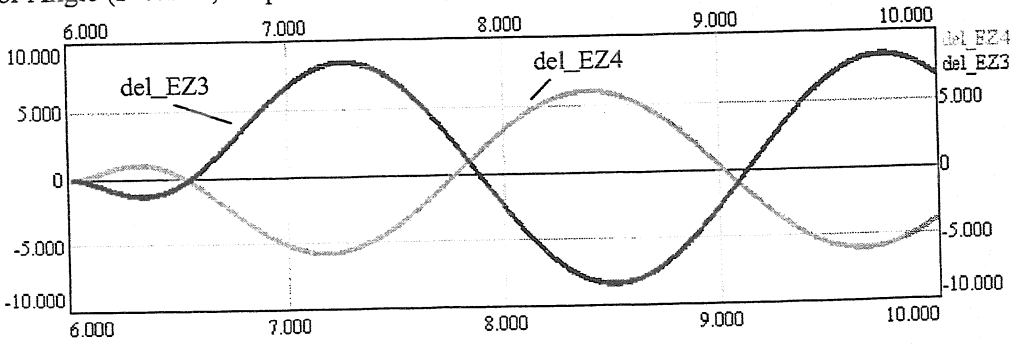
Voltage and current (f=0.2Hz, torque=1.0e+5N.m)



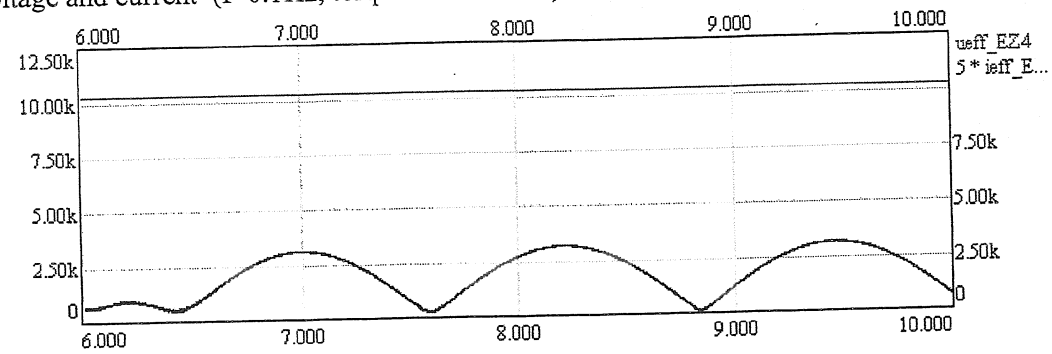
Torque (f=0.1Hz, torque=1.0e+5N.m)



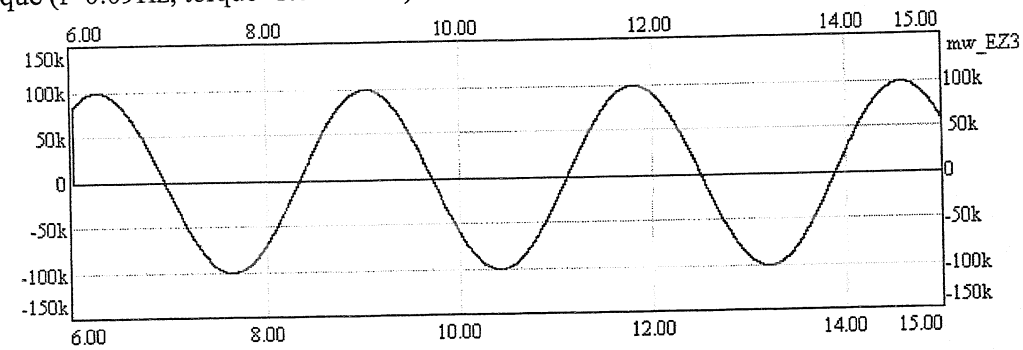
Rotor Angle (f=0.1Hz, torque=1.0e+5N.m)



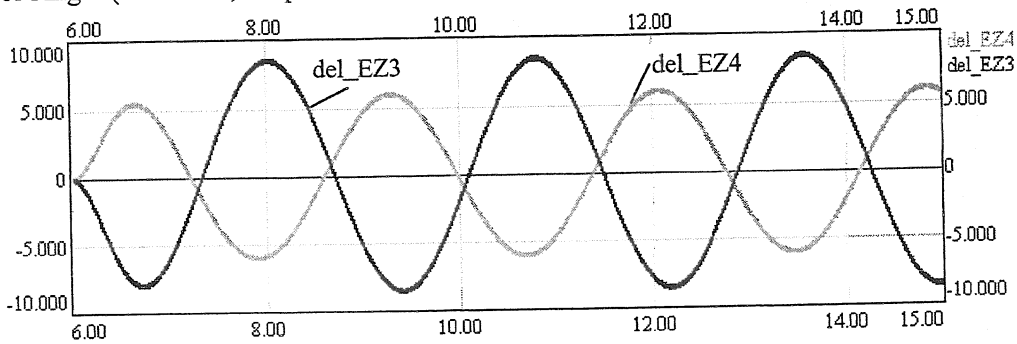
Voltage and current (f=0.1Hz, torque=1.0e+5N.m)



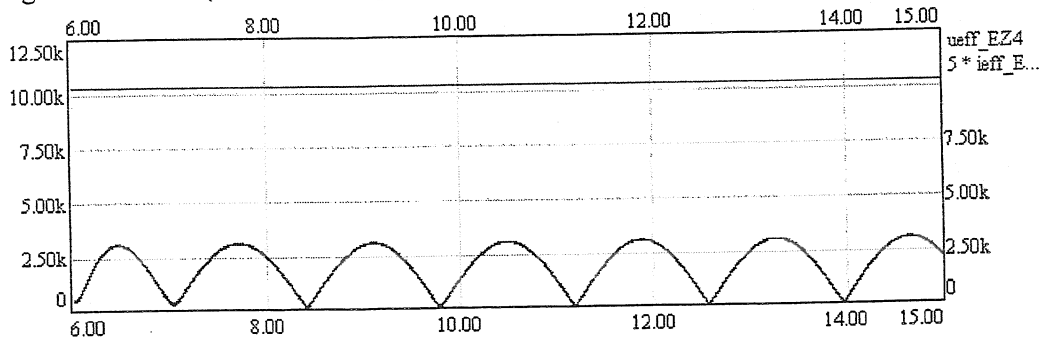
Torque (f=0.09Hz, torque=1.0e+5N.m)



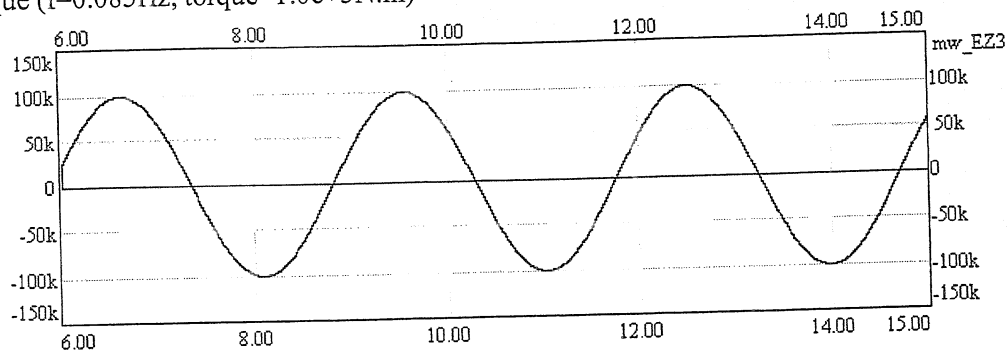
Rotor Angle (f=0.09Hz, torque=1.0e+5N.m)



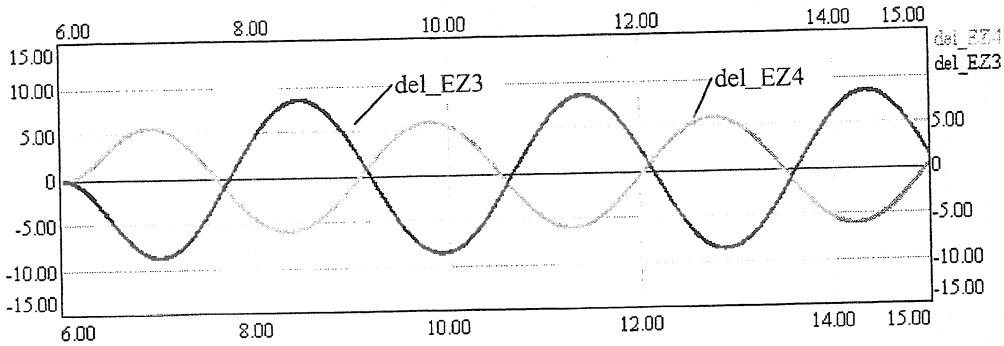
Voltage and current (f=0.09Hz, torque=1.0e+5N.m)



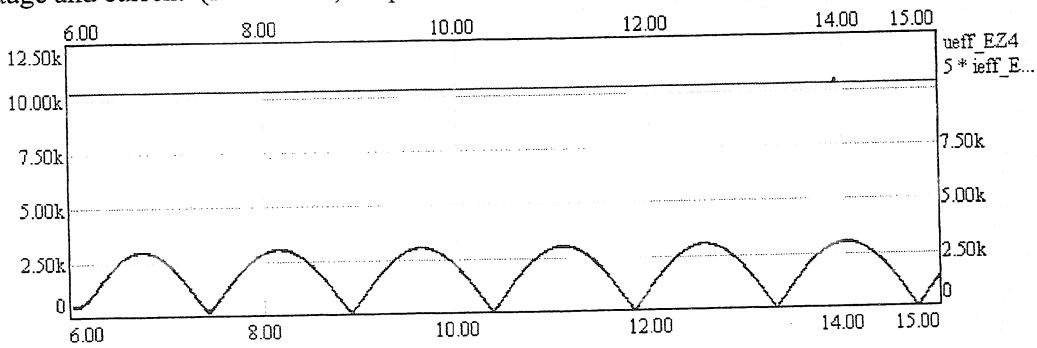
Torque (f=0.085Hz, torque=1.0e+5N.m)



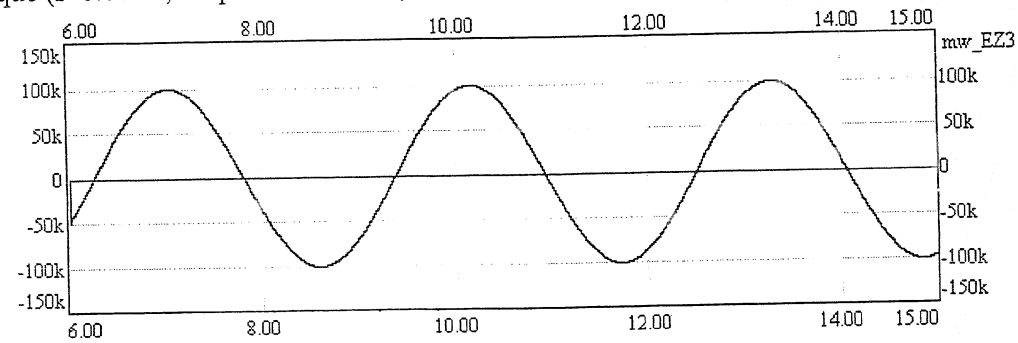
Rotor Angle (f=0.085Hz, torque=1.0e+5N.m)



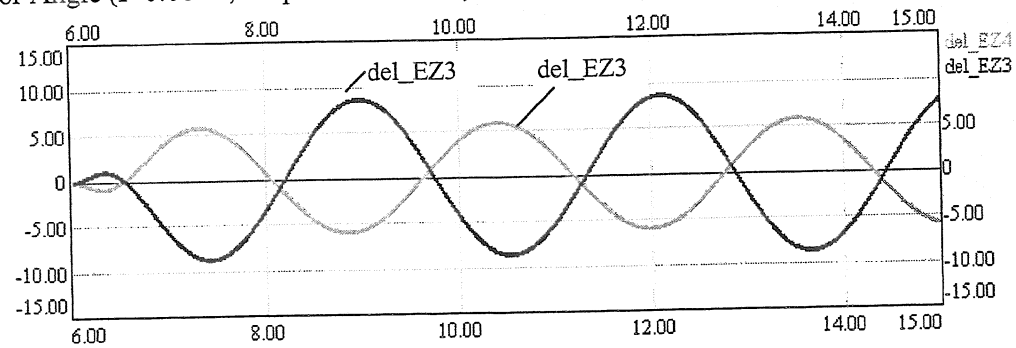
Voltage and current (f=0.085Hz, torque=1.0e+5N.m)



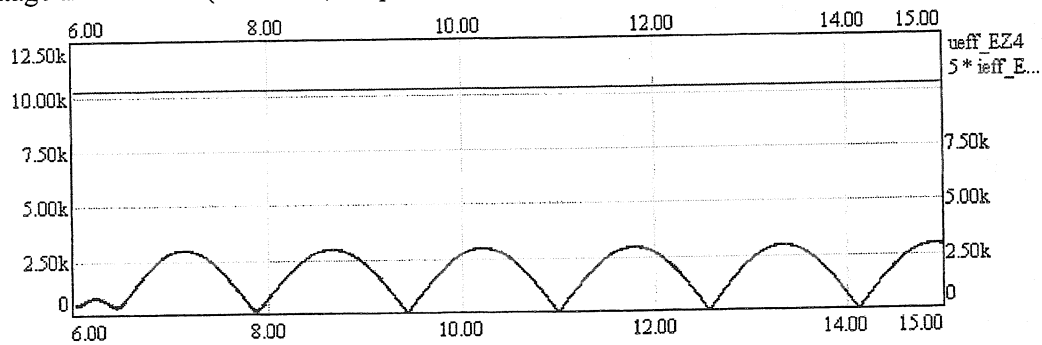
Torque (f=0.08Hz, torque=1.0e+5N.m)



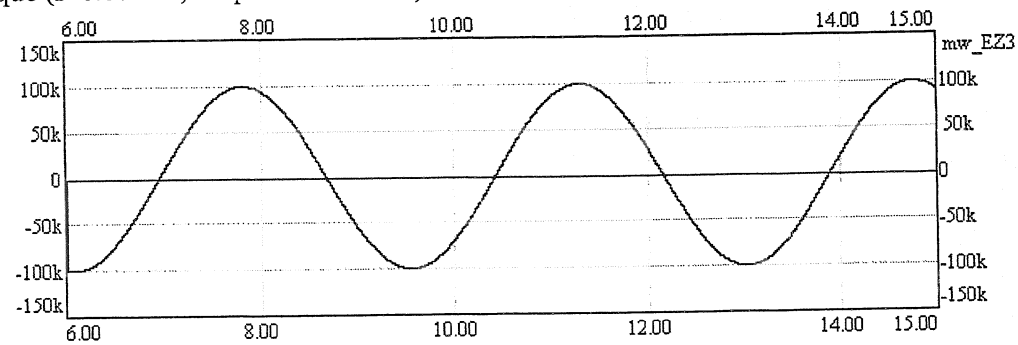
Rotor Angle (f=0.08Hz, torque=1.0e+5N.m)



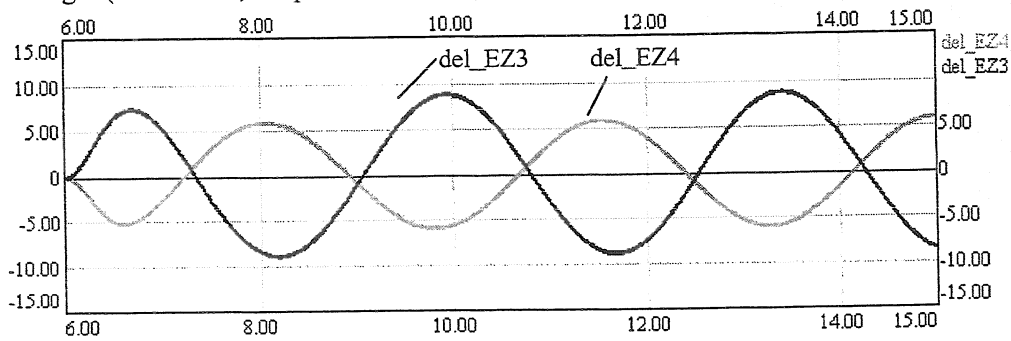
Voltage and current (f=0.08Hz, torque=1.0e+5N.m)



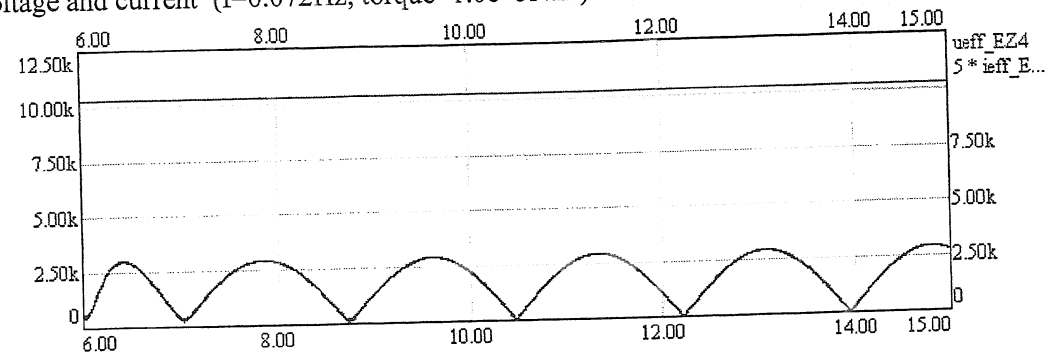
Torque (f=0.072Hz, torque=1.0e+5N.m)



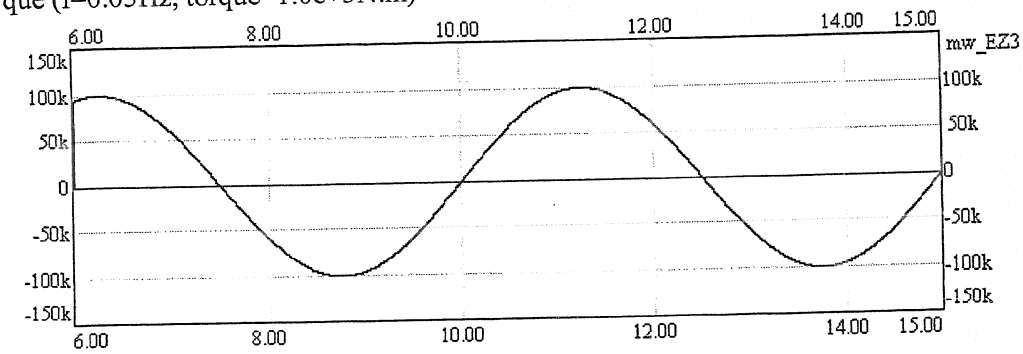
Rotor Angle (f=0.072Hz, torque=1.0e+5N.m)



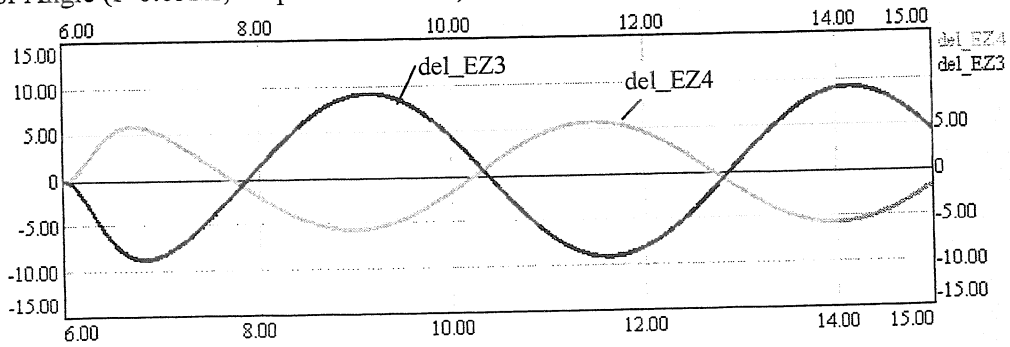
Voltage and current (f=0.072Hz, torque=1.0e+5N.m)



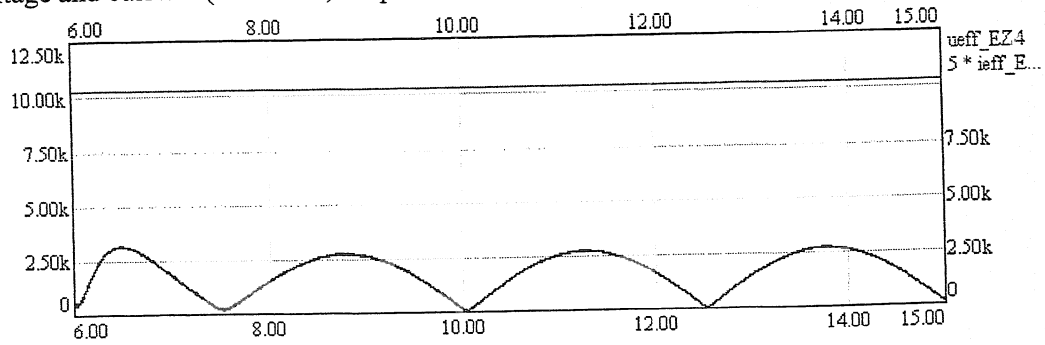
Torque (f=0.05Hz, torque=1.0e+5N.m)



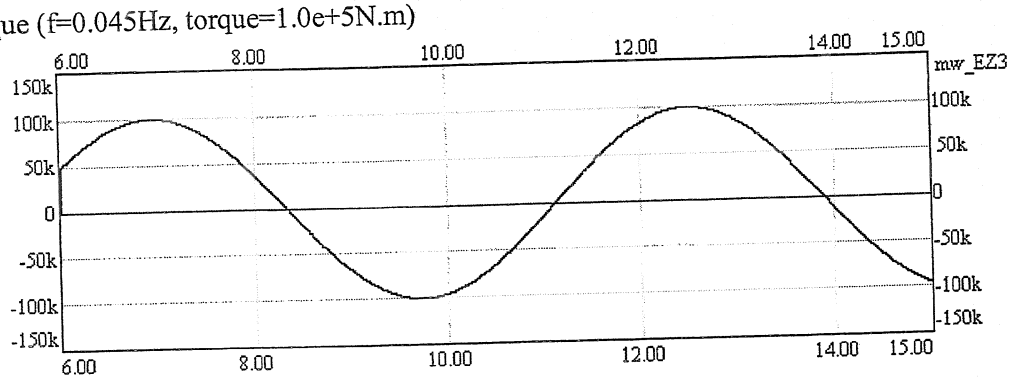
Rotor Angle (f=0.05Hz, torque=1.0e+5N.m)



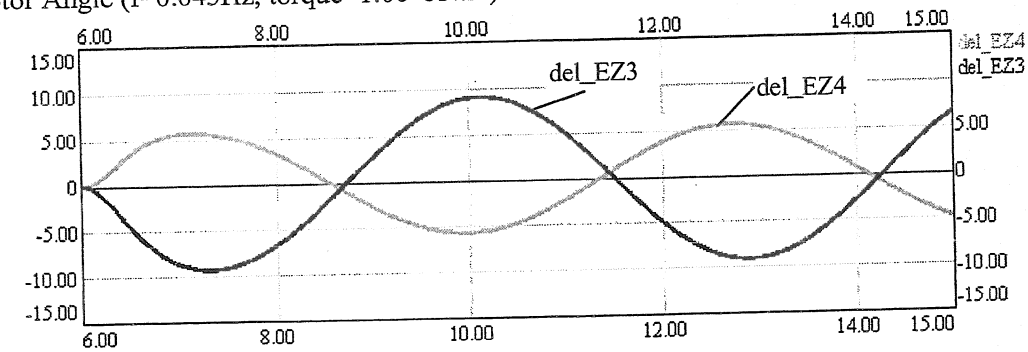
Voltage and current (f=0.05Hz, torque=1.0e+5N.m)



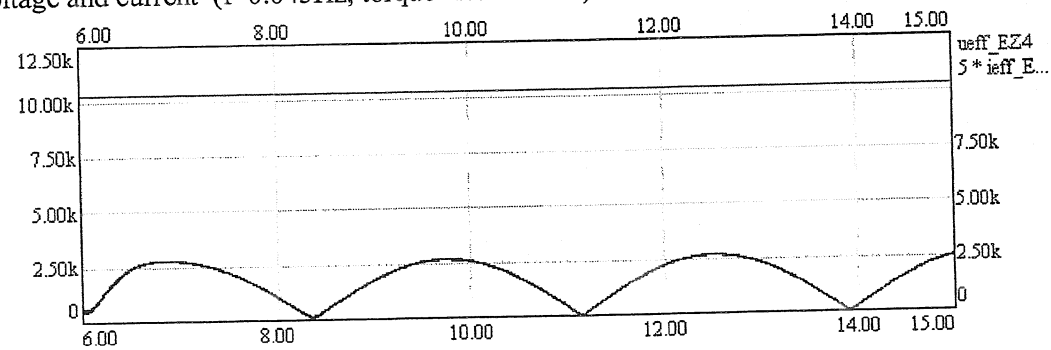
Torque (f=0.045Hz, torque=1.0e+5N.m)



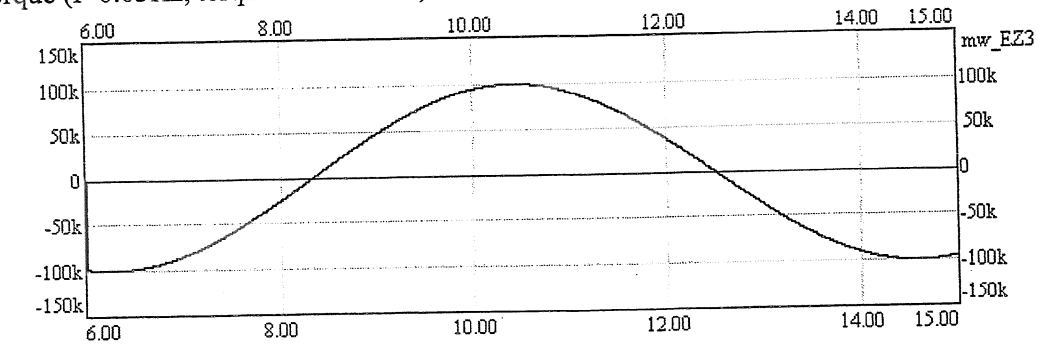
Rotor Angle (f=0.045Hz, torque=1.0e+5N.m)



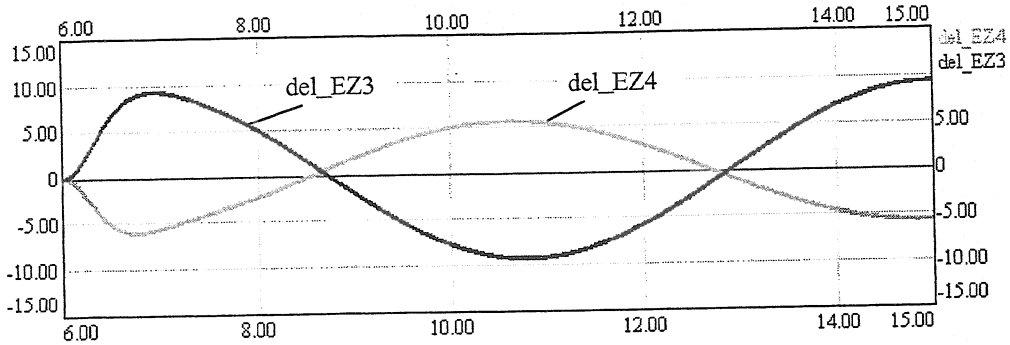
Voltage and current (f=0.045Hz, torque=1.0e+5N.m)



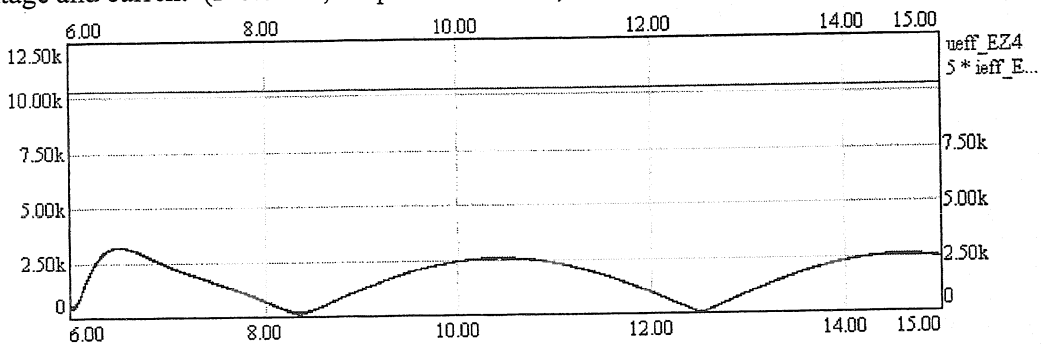
Torque (f=0.03Hz, torque=1.0e+5N.m)



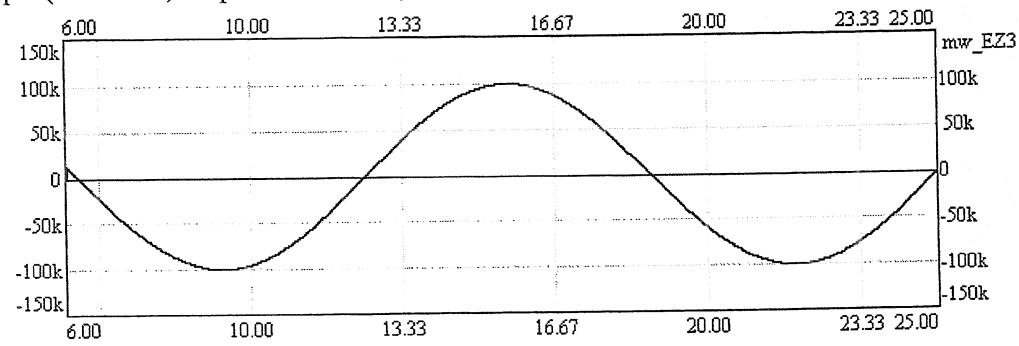
Rotor Angle (f=0.03Hz, torque=1.0e+5N.m)



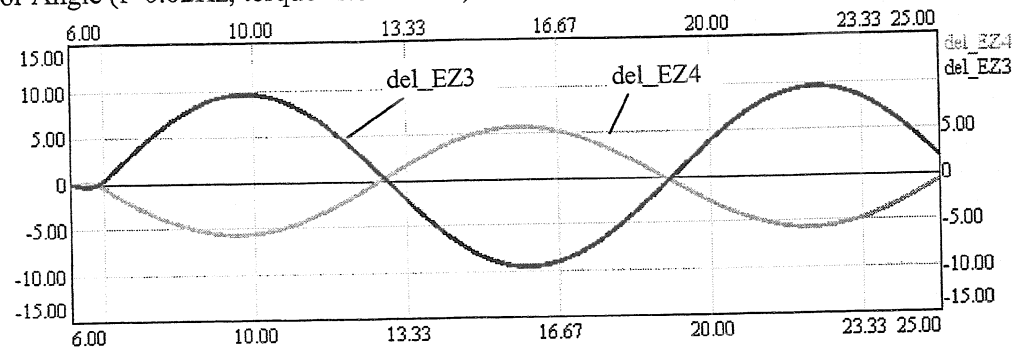
Voltage and current (f=0.03Hz, torque=1.0e+5N.m)



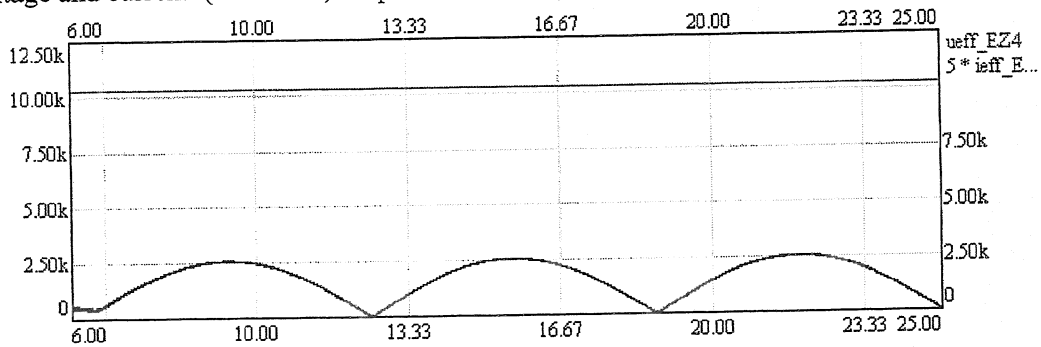
Torque (f=0.02Hz, torque=1.0e+5N.m)



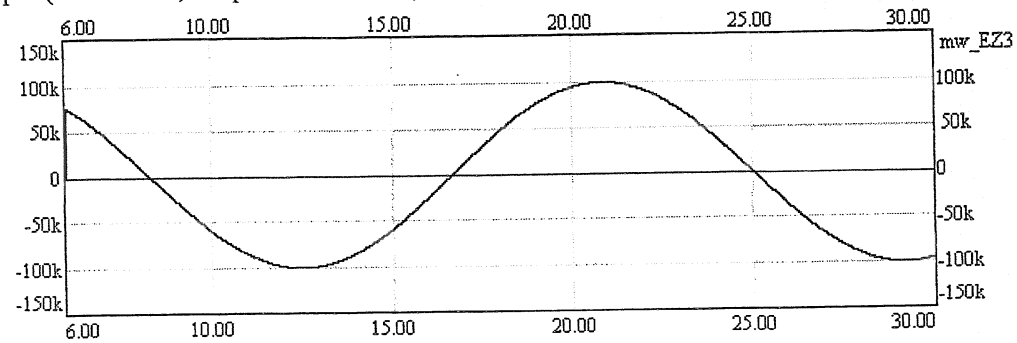
Rotor Angle (f=0.02Hz, torque=1.0e+5N.m)



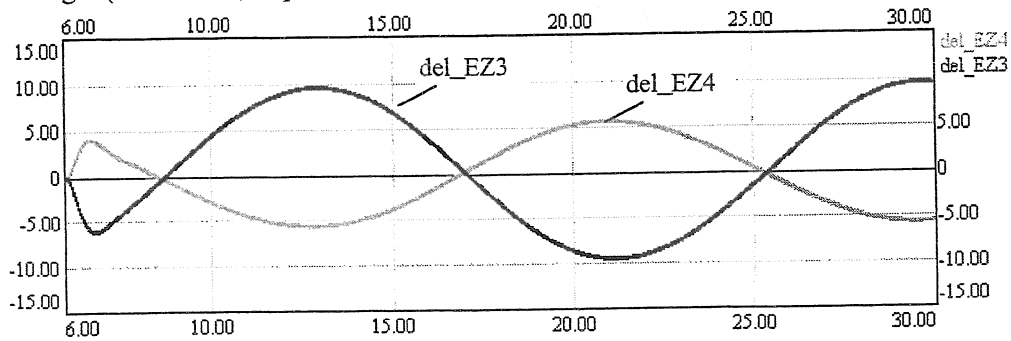
Voltage and current (f=0.02Hz, torque=1.0e+5N.m)



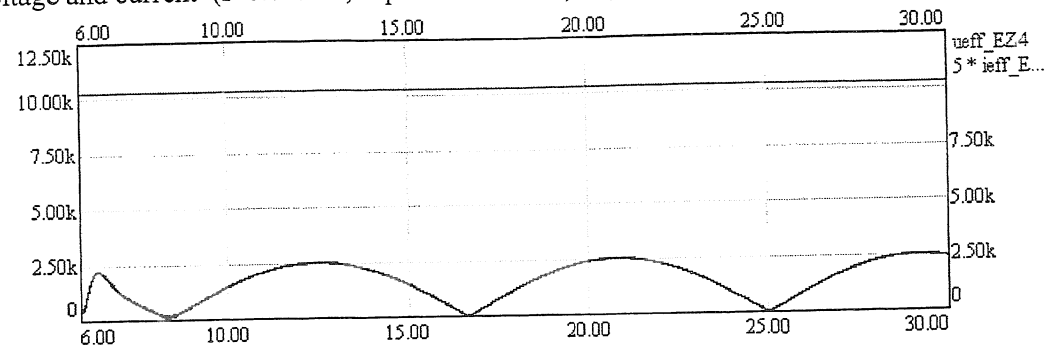
Torque (f=0.015Hz, torque=1.0e+5N.m)



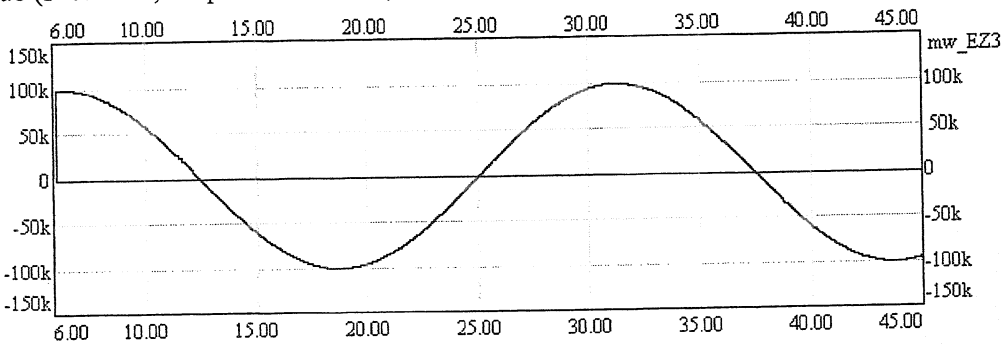
Rotor Angle (f=0.015Hz, toque=1.0e+5N.m)



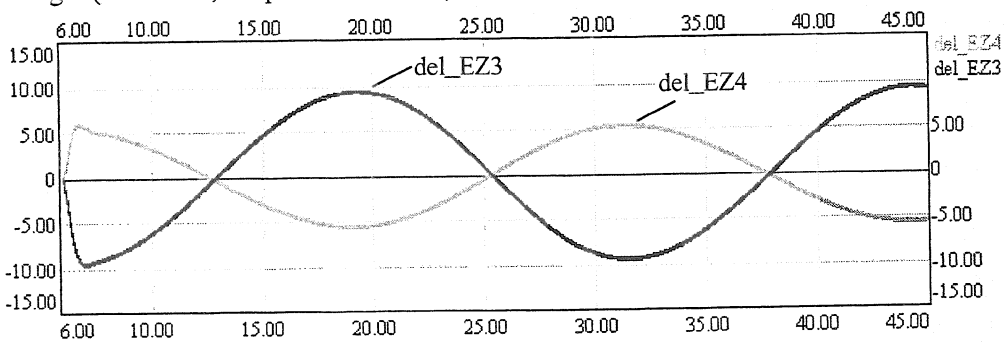
Voltage and current (f=0.015Hz, trque=1.0e+5N.m)



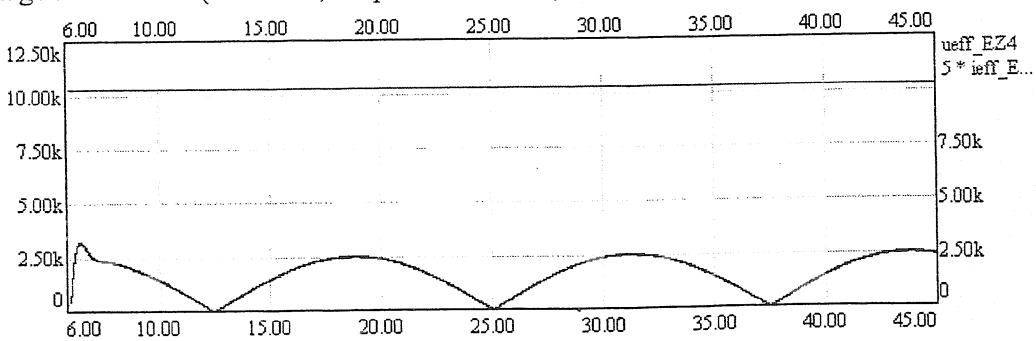
Torque (f=0.01Hz, torque=1.0e+5N.m)



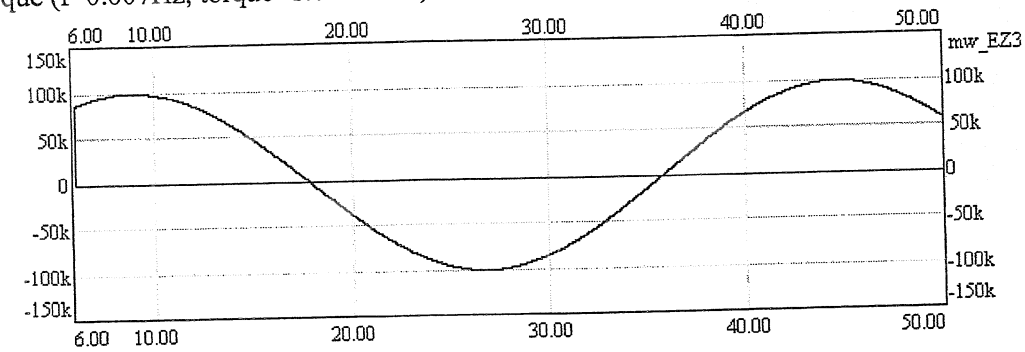
Rotor angle (f=0.01Hz, torque=1.0e+5N.m)



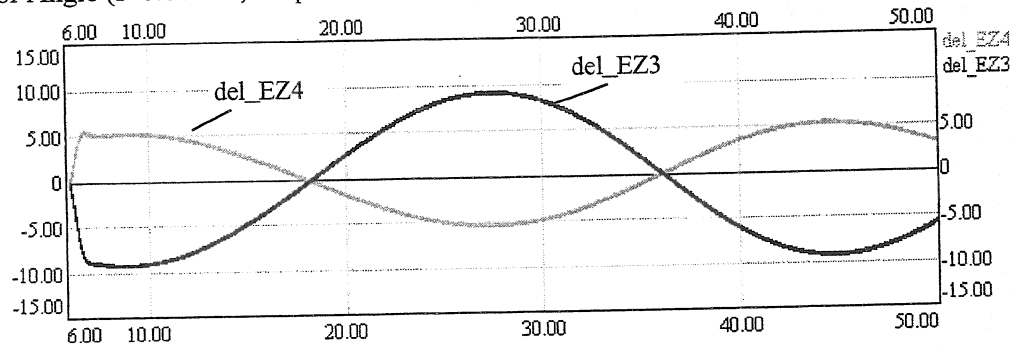
Voltage and current (f=0.01Hz, torque=1.0e+5N.m)



Torque (f=0.007Hz, torque=1.0e+5N.m)

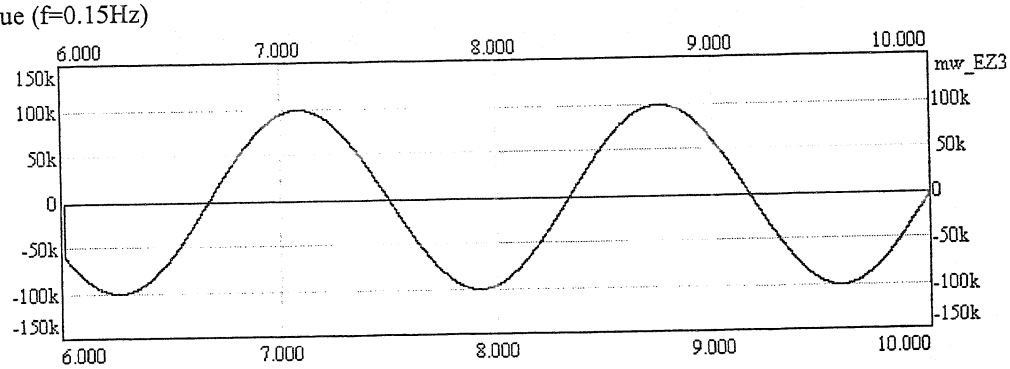


Rotor Angle (f=0.007Hz, torque=1.0e+5N.m)

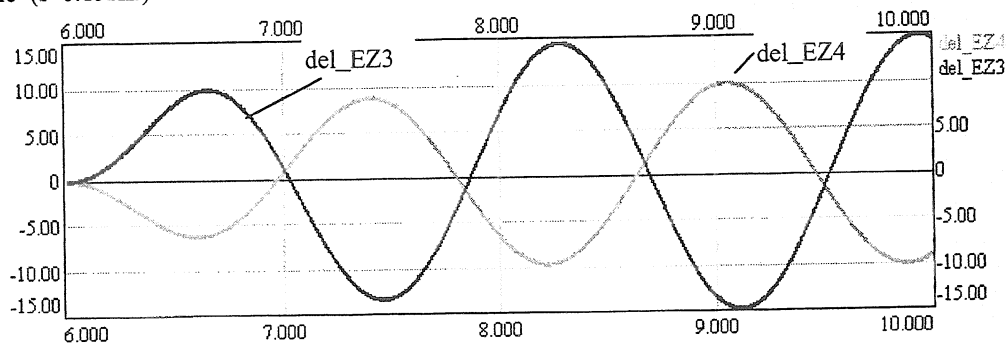


b. Generator Parameters: Rkq*2, Rs*1.3, Ls*1.4

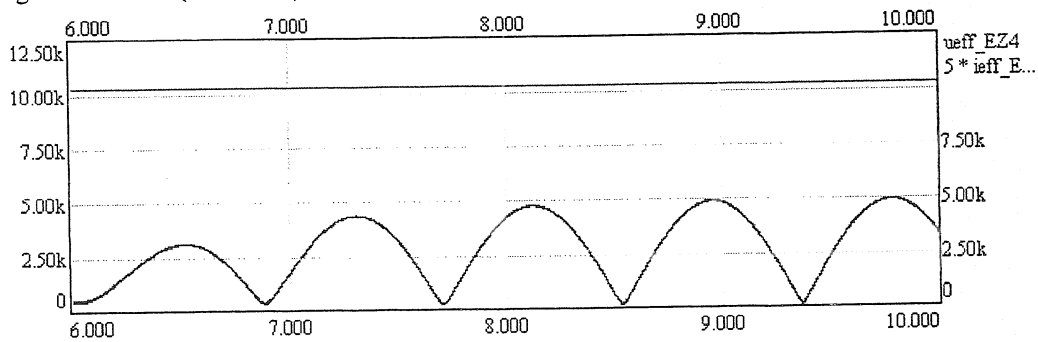
Torque (f=0.15Hz)



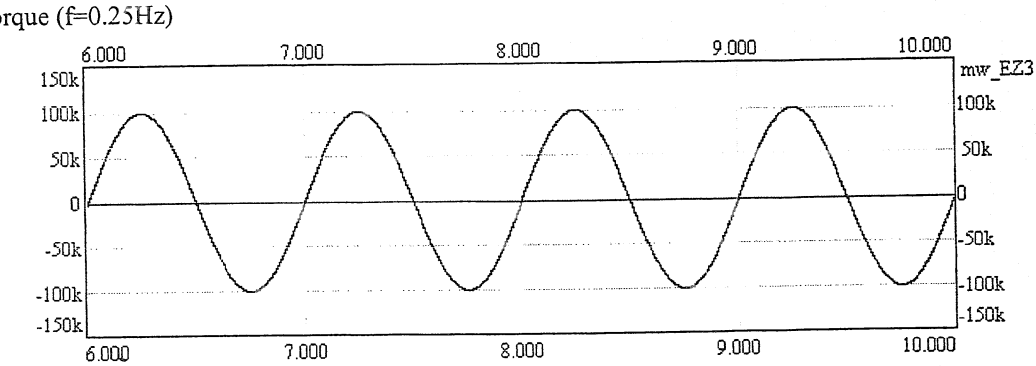
Angle (f=0.15HZ)



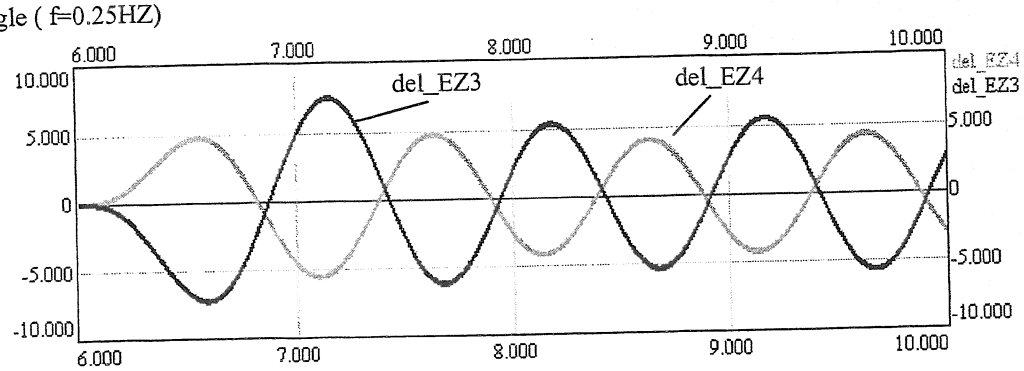
Voltage and current (f=0.15Hz)



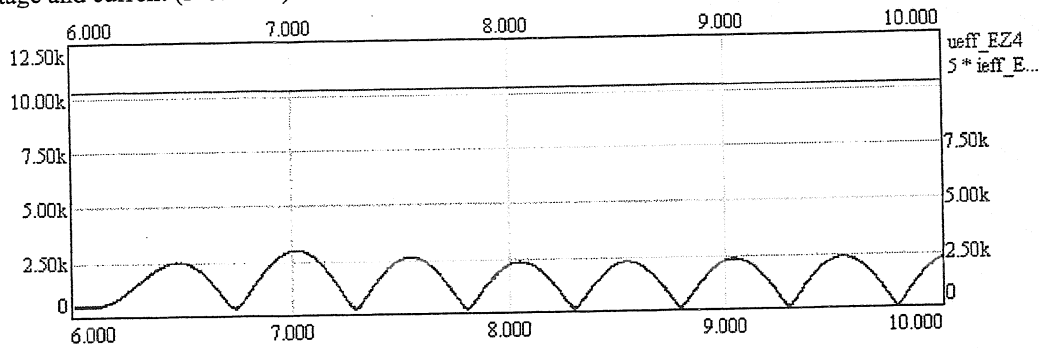
Torque (f=0.25Hz)



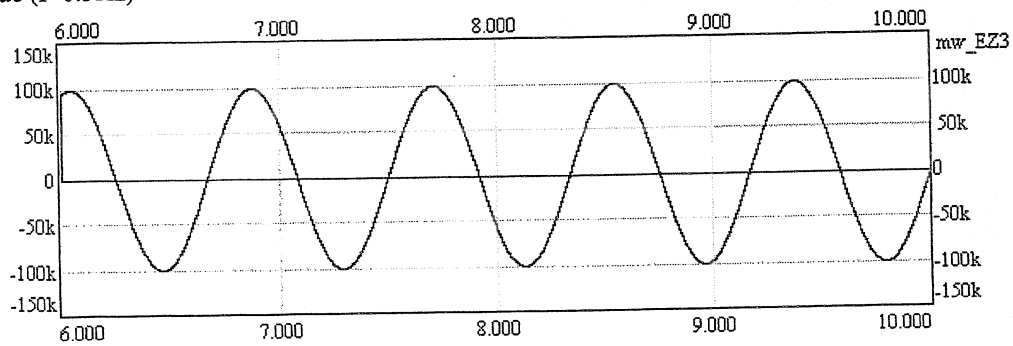
Angle (f=0.25HZ)



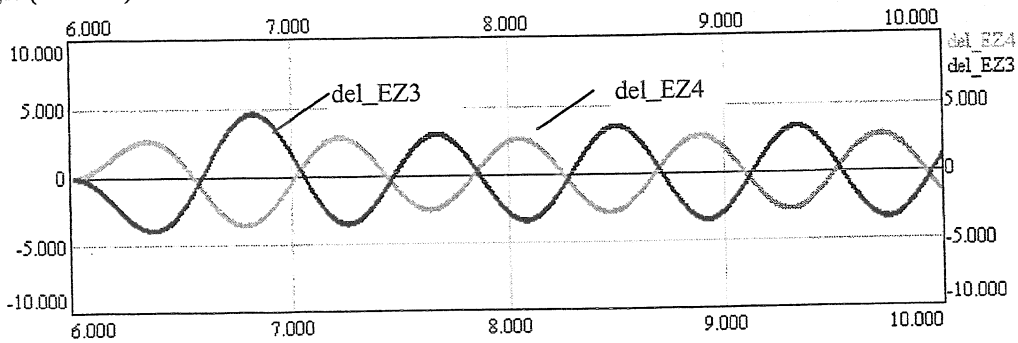
Voltage and current (f=0.25Hz)



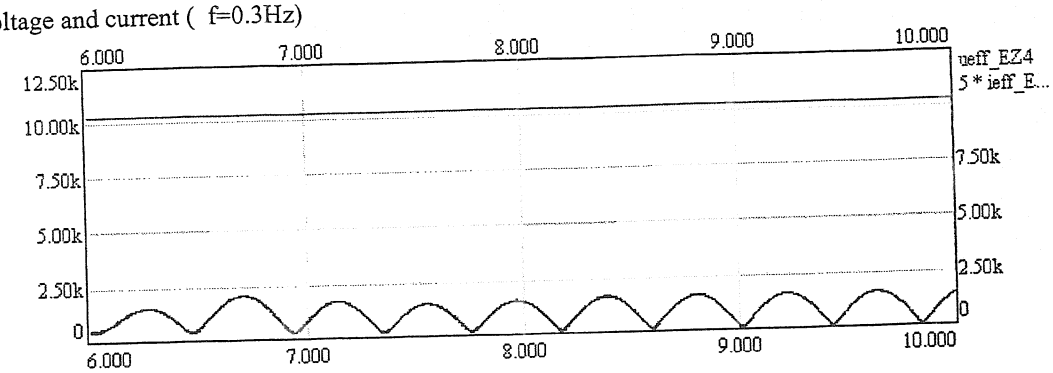
Torque (f=0.3Hz)



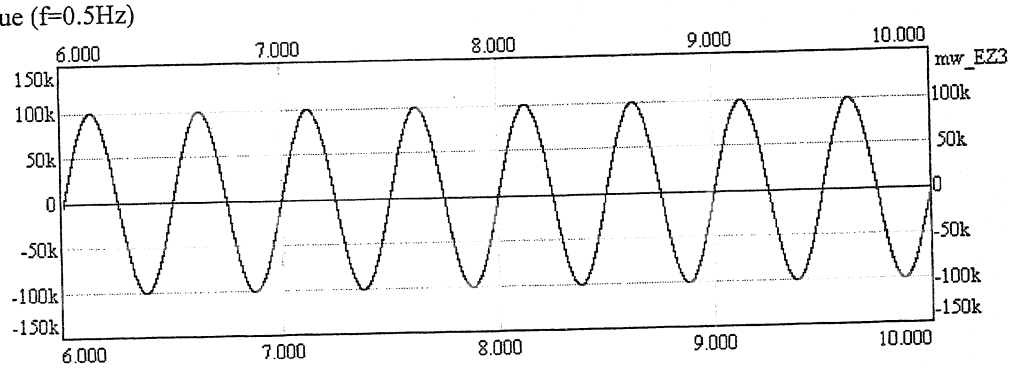
Angle (f=0.3Hz)



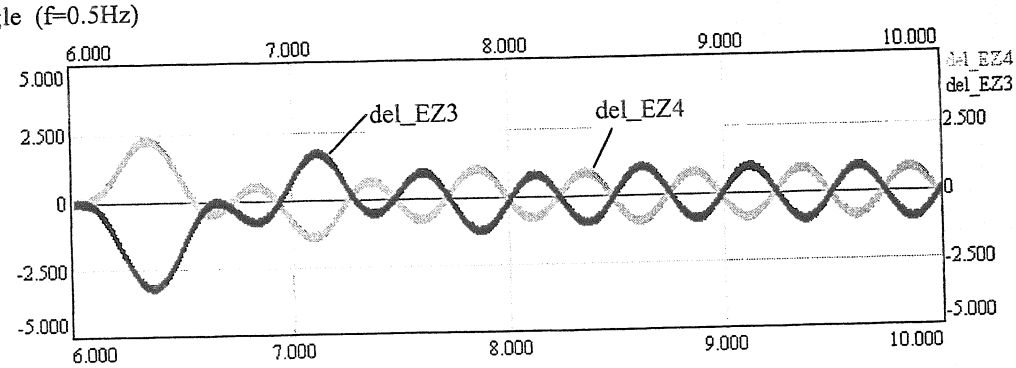
Voltage and current (f=0.3Hz)



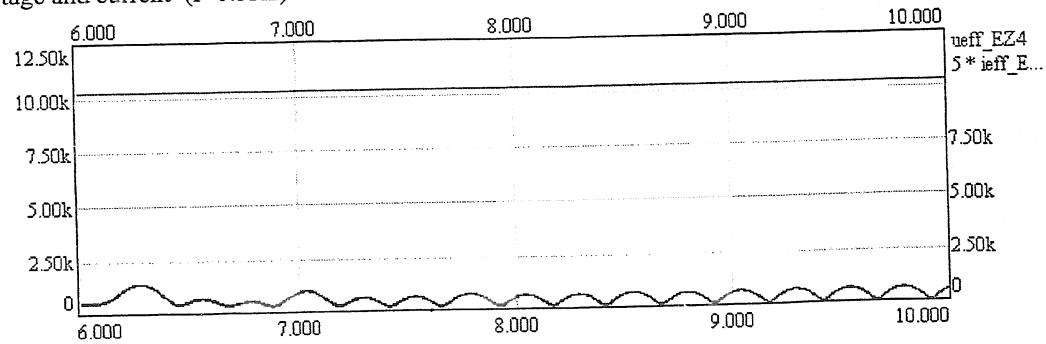
Torque (f=0.5Hz)



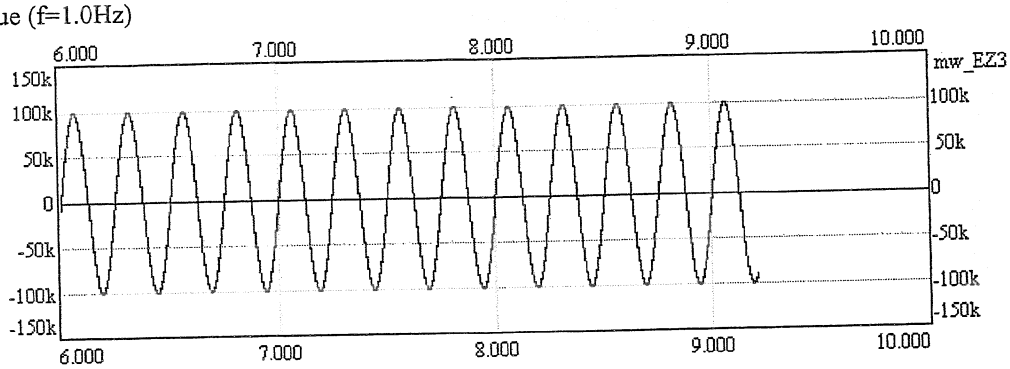
Angle (f=0.5Hz)



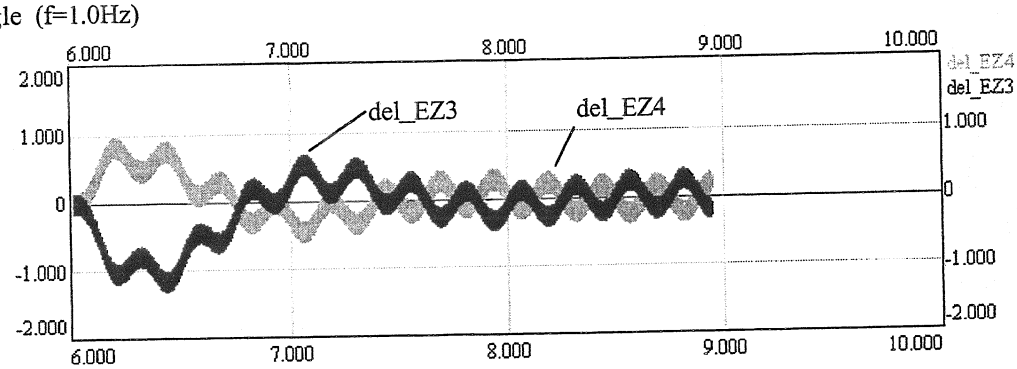
Voltage and current (f=0.5Hz)



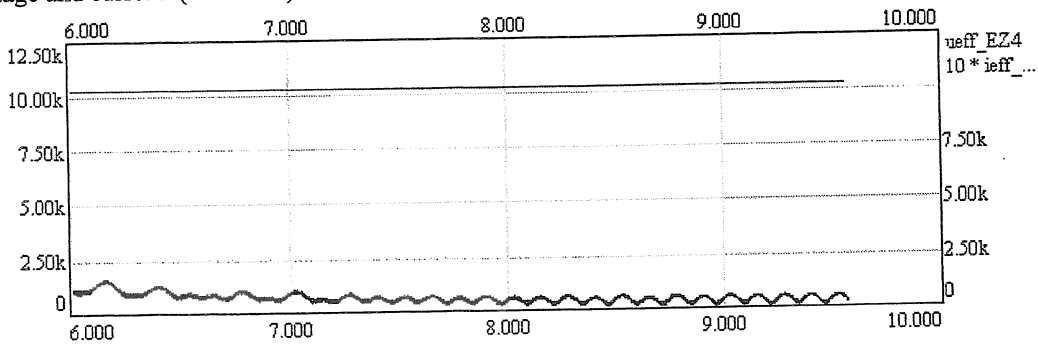
Torque (f=1.0Hz)



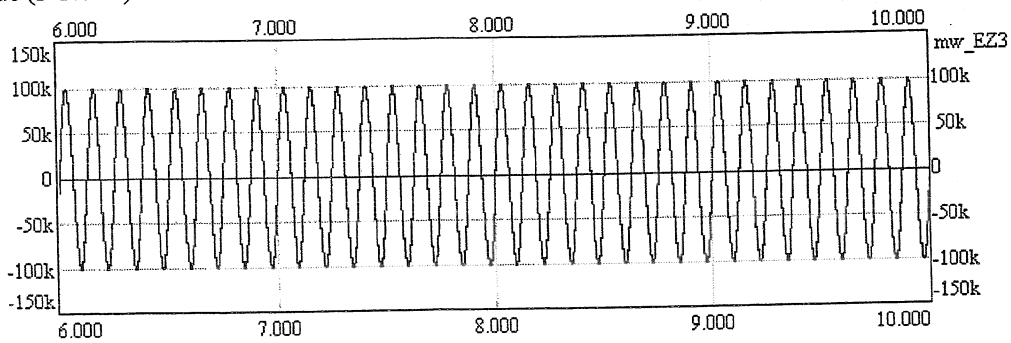
Angle (f=1.0Hz)



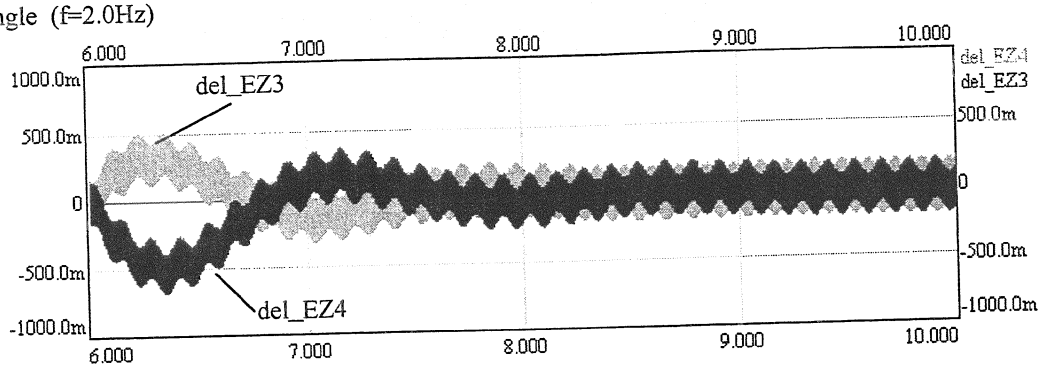
Voltage and current (f=0.15Hz)



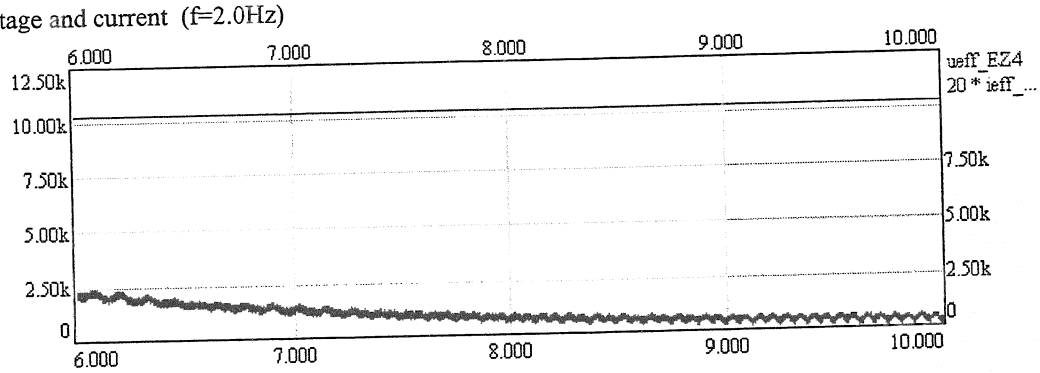
Torque (f=2.0Hz)



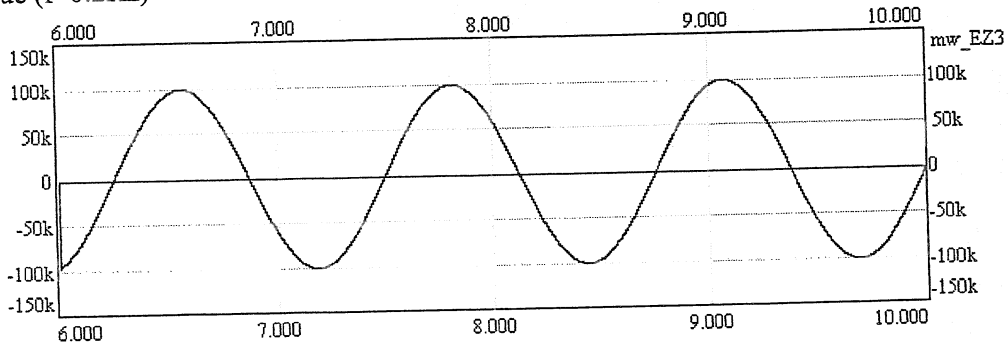
Angle (f=2.0Hz)



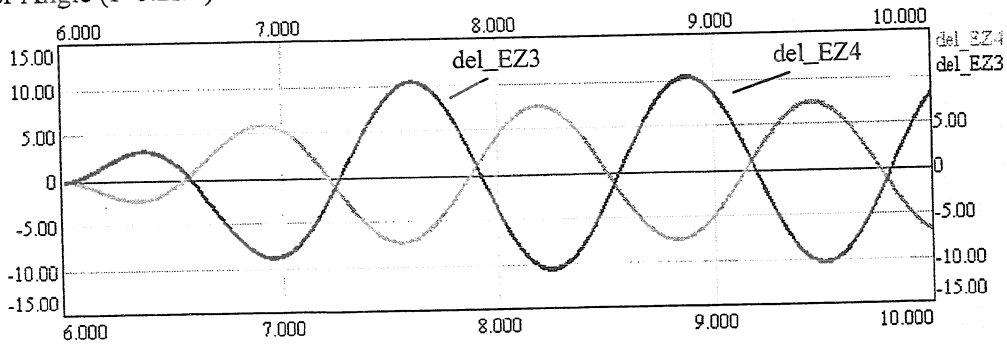
Voltage and current (f=2.0Hz)



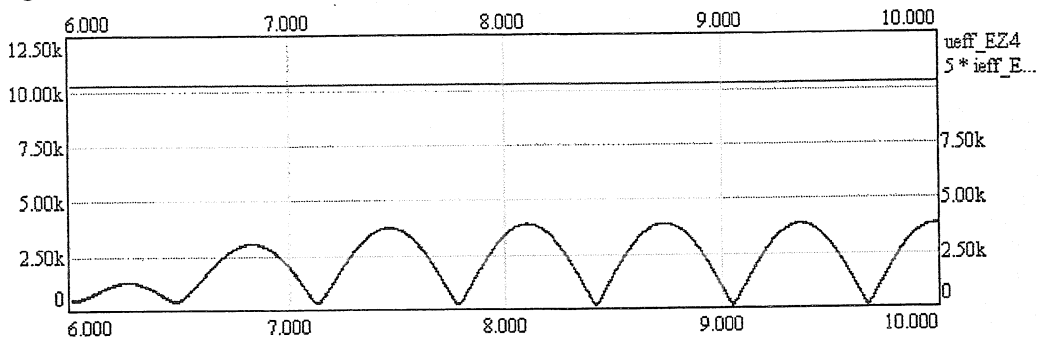
Torque (f=0.2Hz)



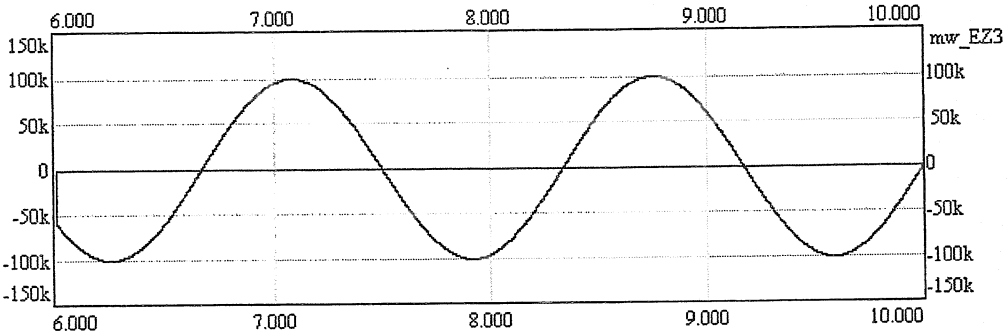
Rotor Angle (f=0.2Hz)



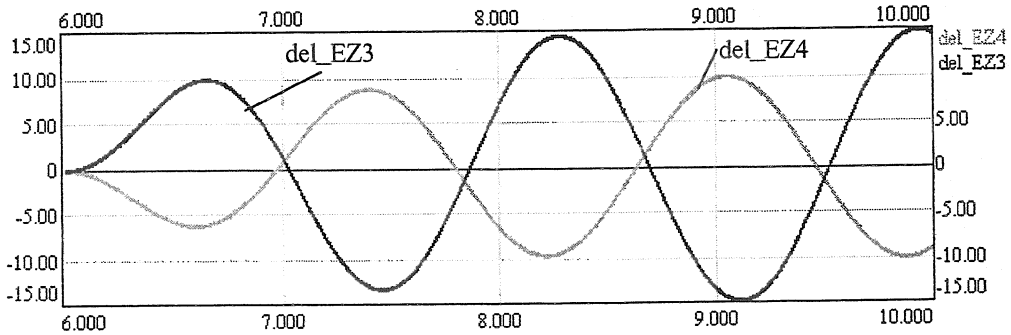
Voltage and current (f=0.2Hz)



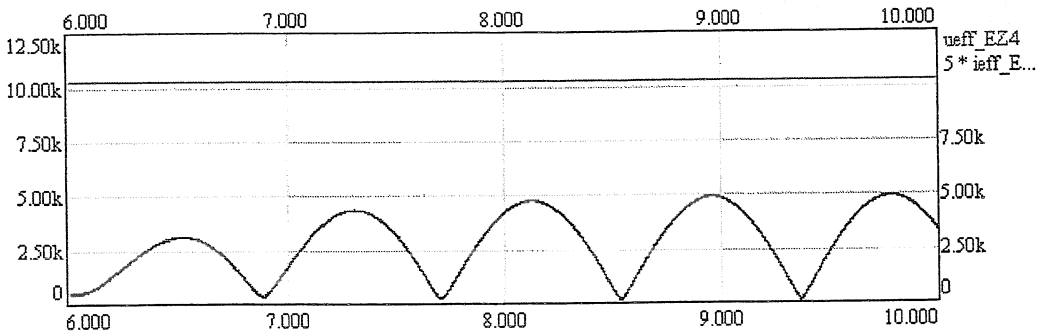
Torque (f=0.15Hz)



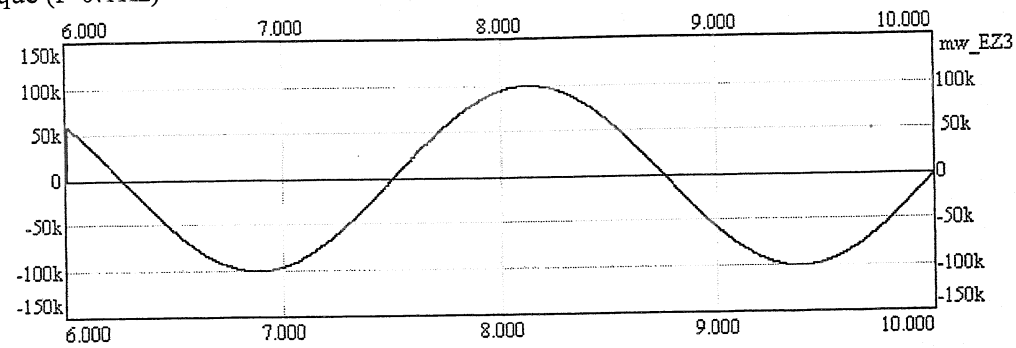
Angle (f=0.15HZ)



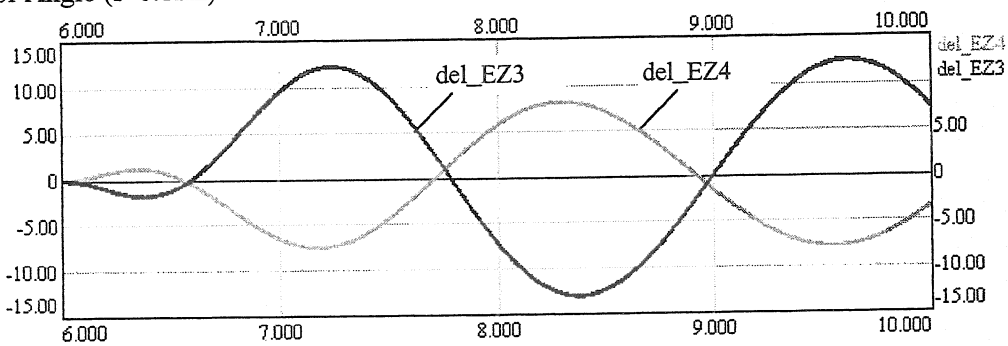
Voltage and current (f=0.15Hz)



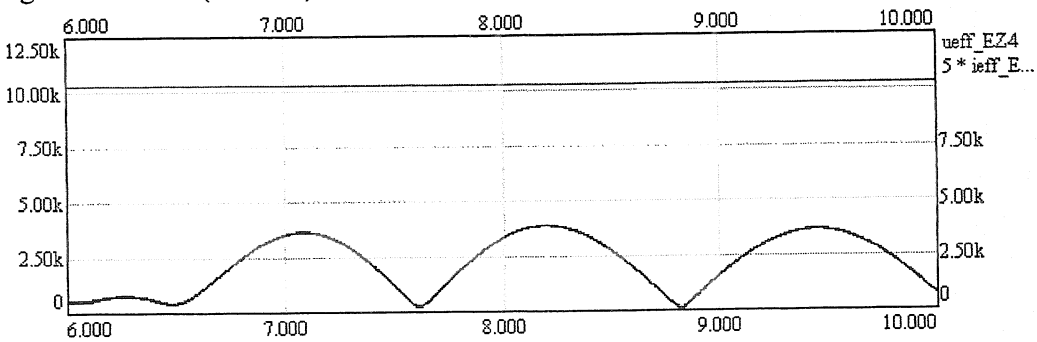
Torque (f=0.1Hz)



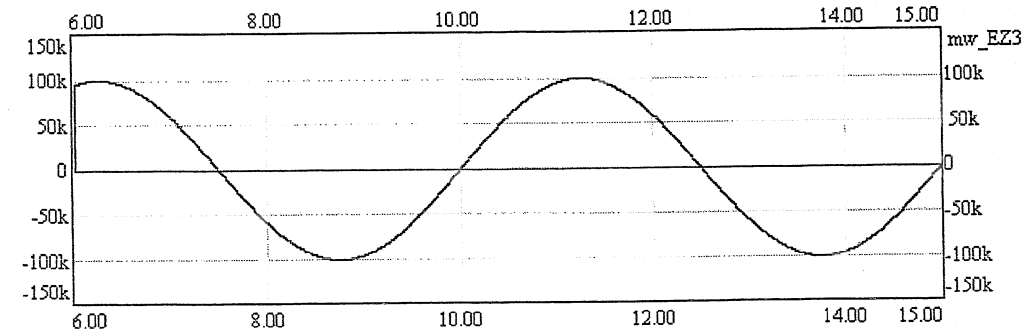
Rotor Angle (f=0.1Hz)



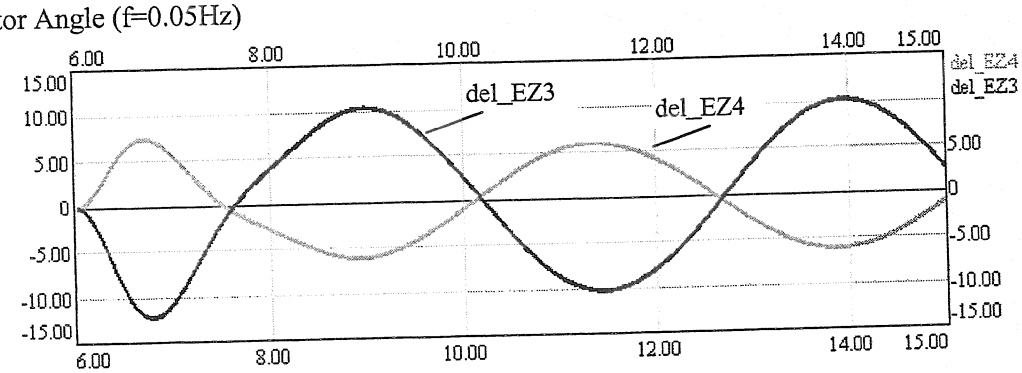
Voltage and current (f=0.1Hz)



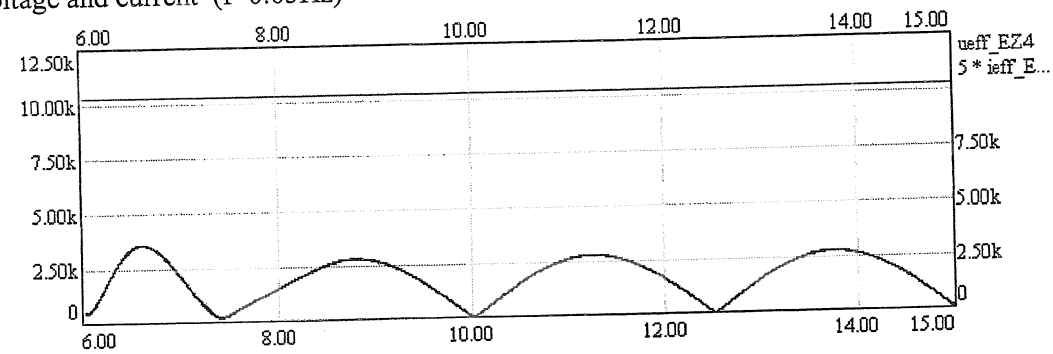
Torque (f=0.05Hz)



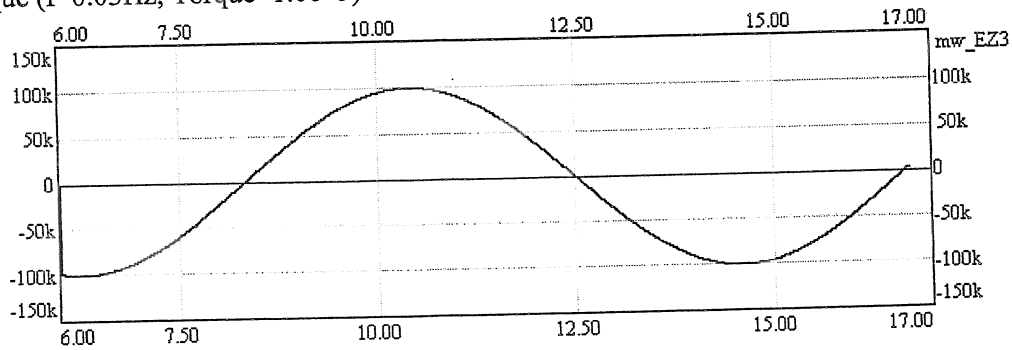
Rotor Angle (f=0.05Hz)



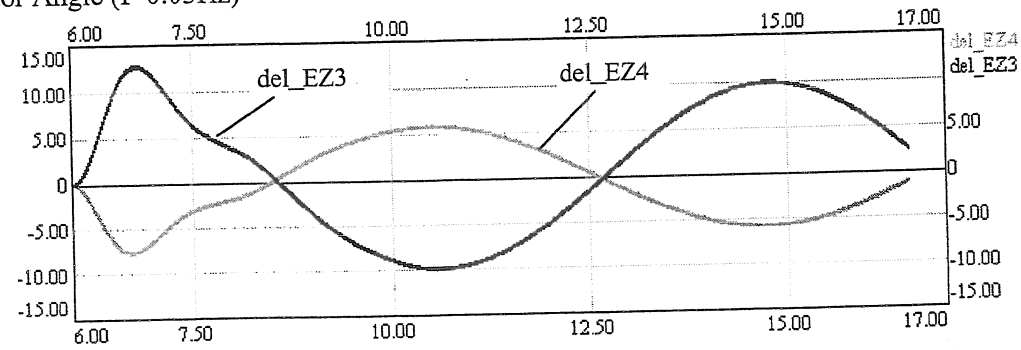
Voltage and current (f=0.05Hz)



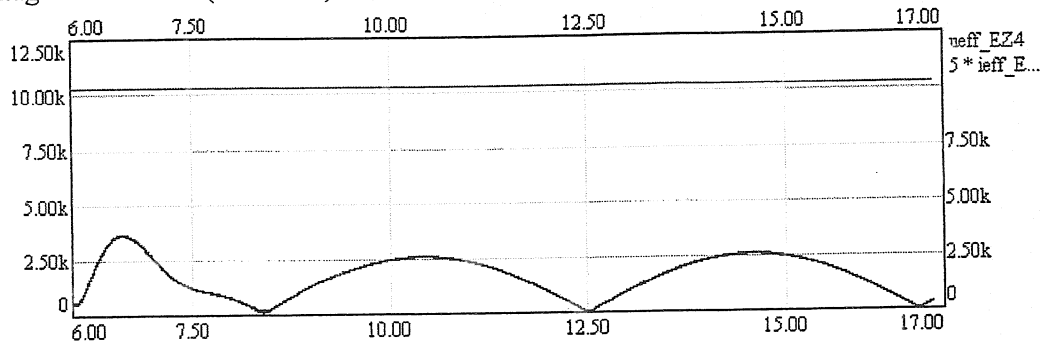
Torque (f=0.03Hz, Torque=1.0e+5)



Rotor Angle (f=0.03Hz)

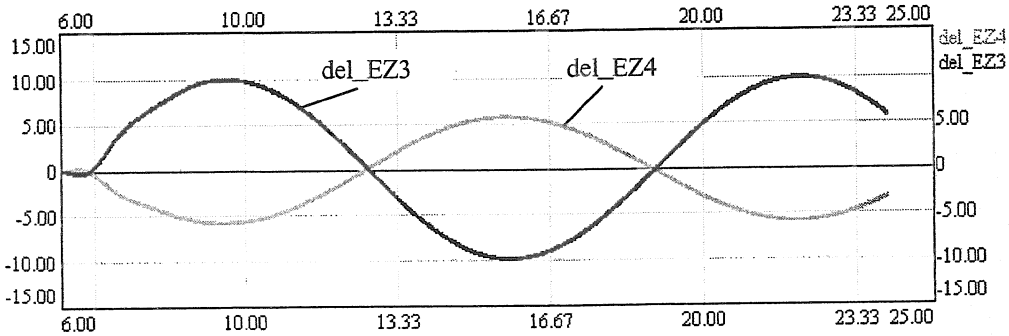


Voltage and current (f=0.03Hz)

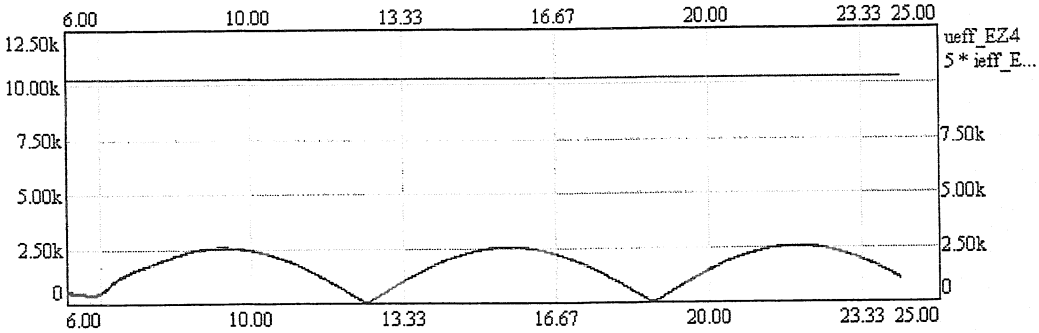


Torque (f=0.02Hz)

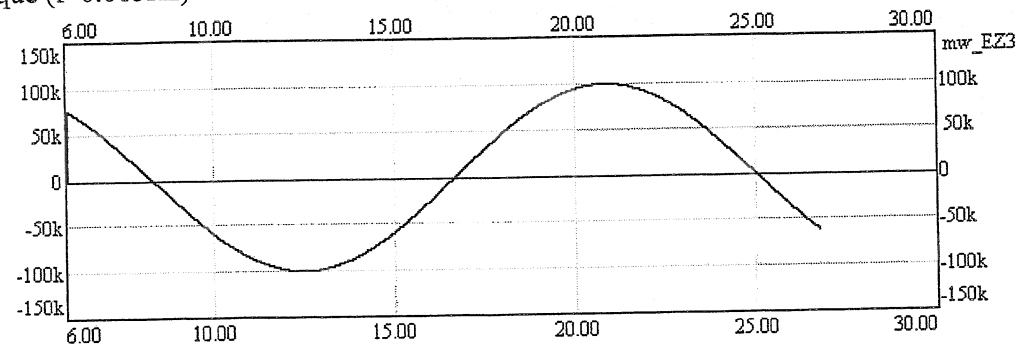
Rotor Angle (f=0.02Hz)



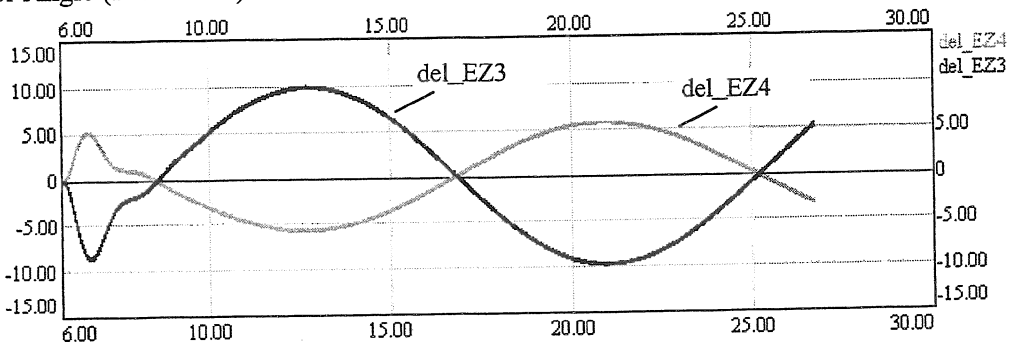
Voltage and current (f=0.02Hz)



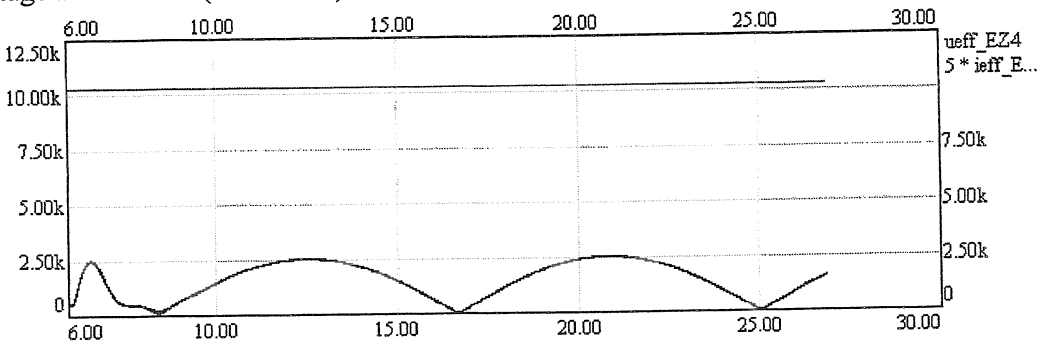
Torque (f=0.015Hz)



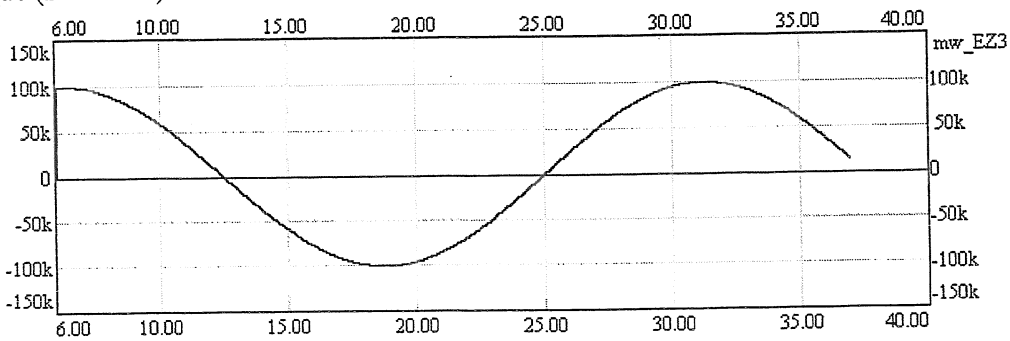
Rotor Angle (f=0.015Hz)



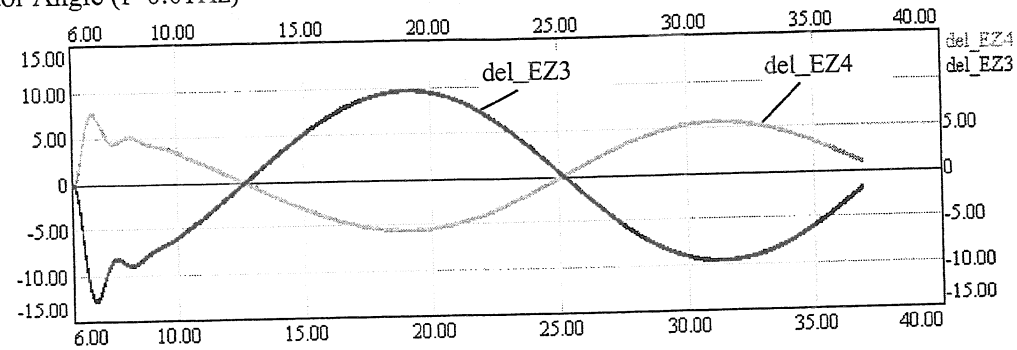
Voltage and current (f=0.015Hz)



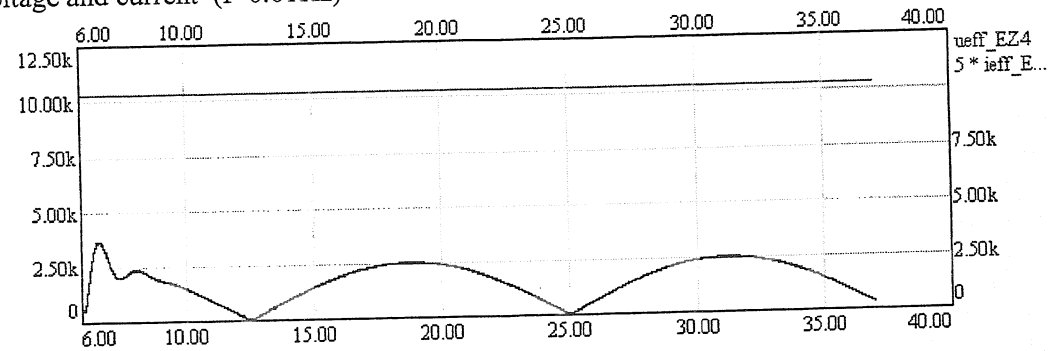
Torque (f=0.01Hz)



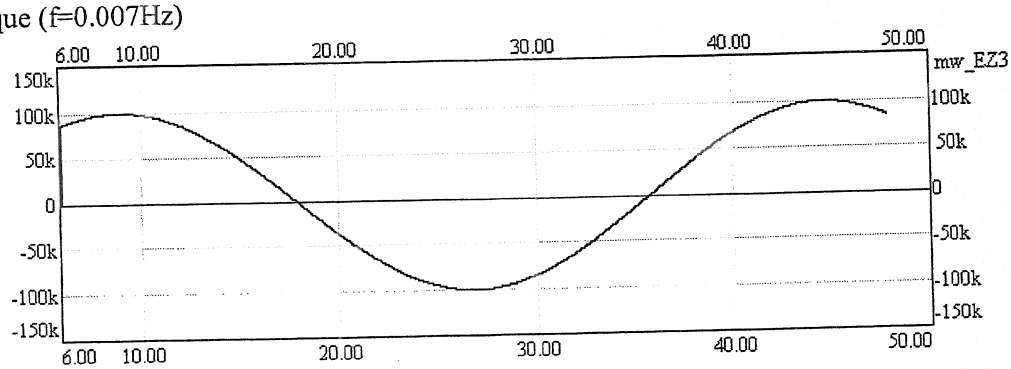
Rotor Angle (f=0.01Hz)



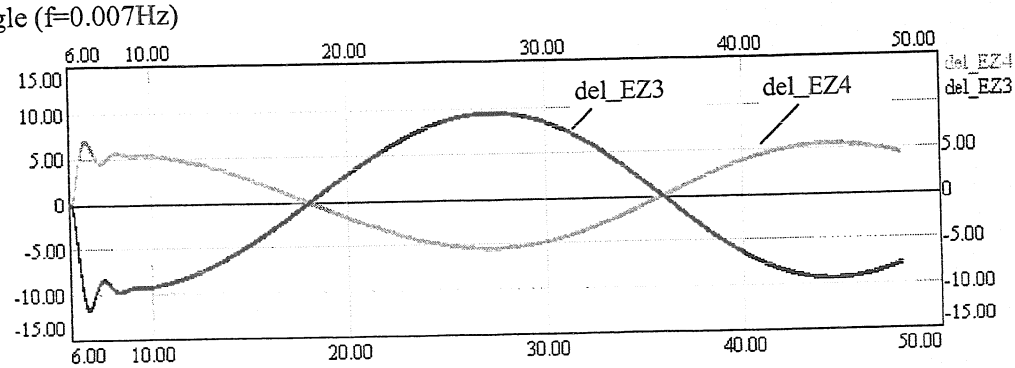
Voltage and current (f=0.01Hz)



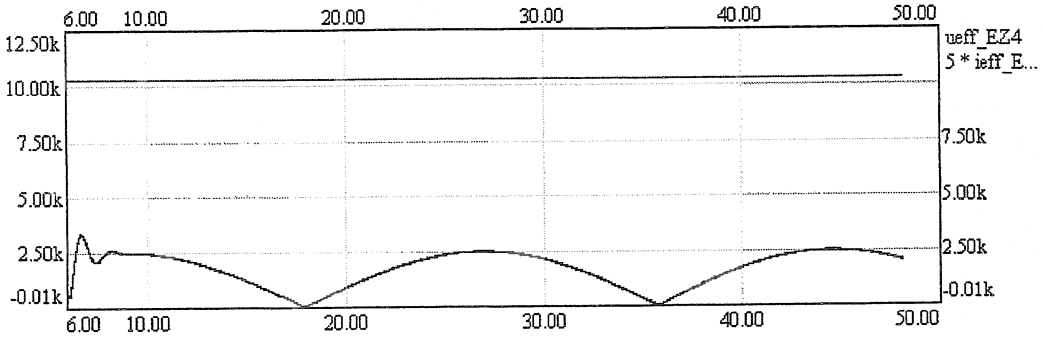
Torque (f=0.007Hz)



Angle (f=0.007Hz)



Voltage and current (f=0.007Hz)

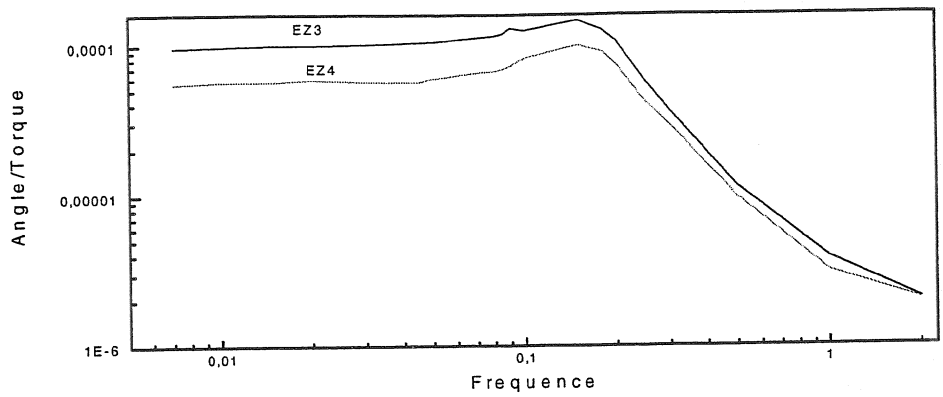


(C) Summary (Rotor Angle/T--Frequency in Torque=1e+5N.m and applied at EZ3)

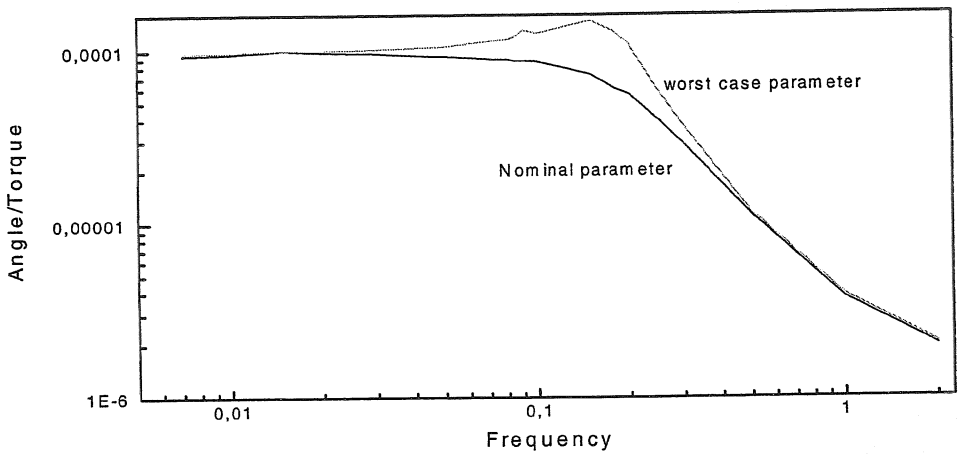
Angle/Torque in Different Frequence

frequence (HZ)	normal parameters		worst parameters	
	EZ3	EZ4	EZ3	EZ4
0.007	9.43e-5	5.25e-5	9.62e-5	5.49e-5
0.01	9.6e-5	5.62e-5	9.79e-5	5.66e-5
0.015	9.98e-5	5.66e-5	9.98e-5	5.66e-5
0.02	9.79e-5	5.66e-5	9.98e-5	5.85e-5
0.03	9.62e-5	5.25e-5	10.15 e-5	5.66 e-5
0.045	9.26e-5	5.66e-5	10.42e-5	5.65e-5
0.05	9.26e-5	5.66e-5	10.52e-5	5.98e-5
0.072	8.91e-5	5.66e-5	11.31e-5	6.57e-5
0.08	8.88e-5	5.98e-5	11.55e-5	6.69e-5
0.085	8.71e-5	5.98e-5	11.96e-5	6.92e-5
0.09	8.703e-5	6.046e-5	13.04e-5	7.28e-5
0.1	8.589e-5	6.046e-5	12.49e-5	8.19e-5
0.15	7.24e-5	5.62e-5	14.69e-5	9.97e-5
0.18	5.98e-5	5.06e-5	12.69e-5	9.07e-5
0.2	5.563e-5	4.825e-5	10.69e-5	7.43e-5
0.25	3.899e-5	3.421e-5	5.67e-5	4.1e-5
0.3	2.849e-5	2.730e-5	3.617e-5	2.893e-5
0.5	1.107e-5	0.987e-5	1.141e-5	0.963e-5
1.0	0.372e-5	0.372e-5	0.385e-5	0.312e-5
2.0	0.1975e-5	0.2e-5	0.204e-5	0.20e-5

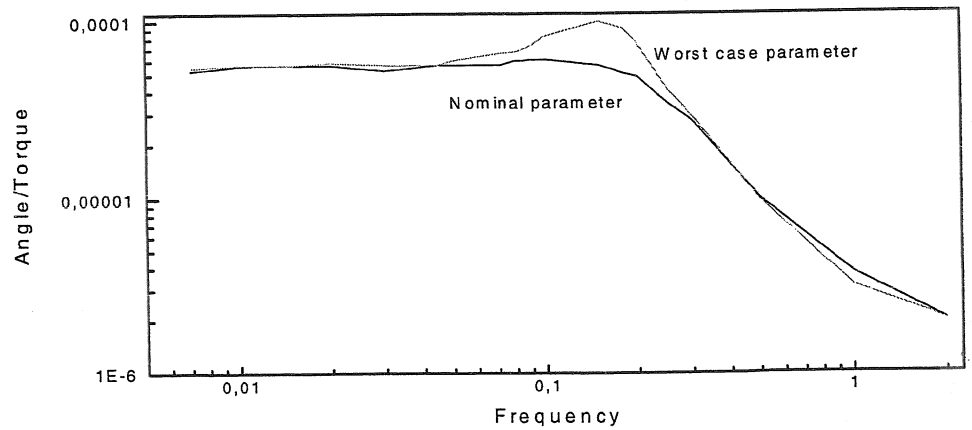
EZ3 and EZ4 Angle/Torque--Frequence (modifated parameter)



Angle/Torque----Frequence of Generators EZ3



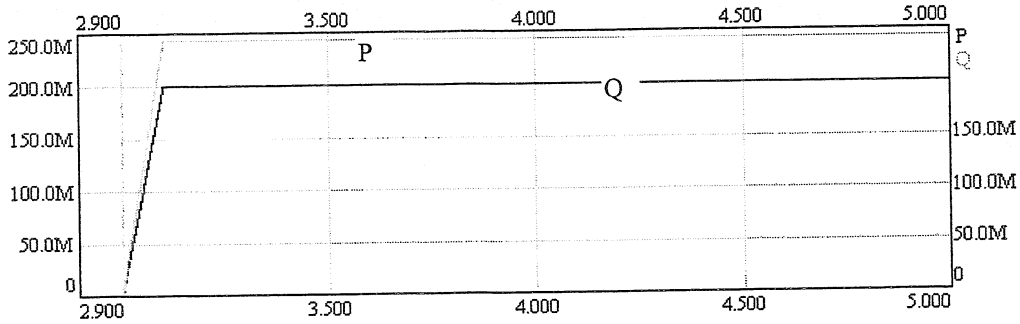
Angle/Torque----Frequence of Generator EZ4



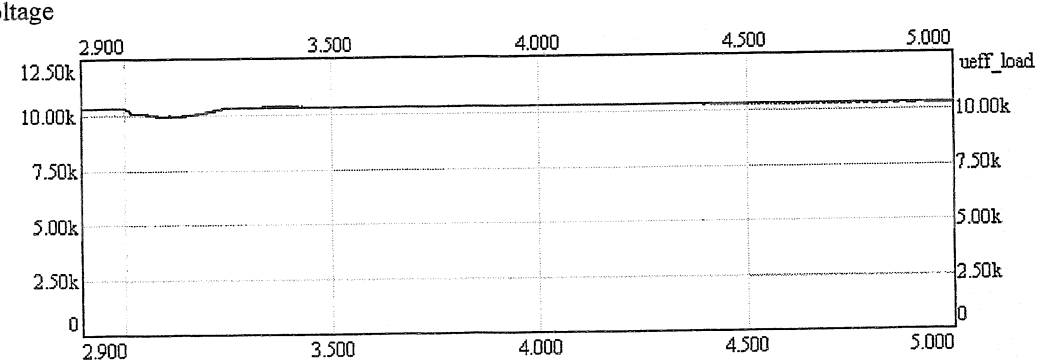
7. Dynamic response on step load and simulation of the current in the paralleling switch

(1) Worst parameter (Rkq*2, Rs*2, Ls*1.4)

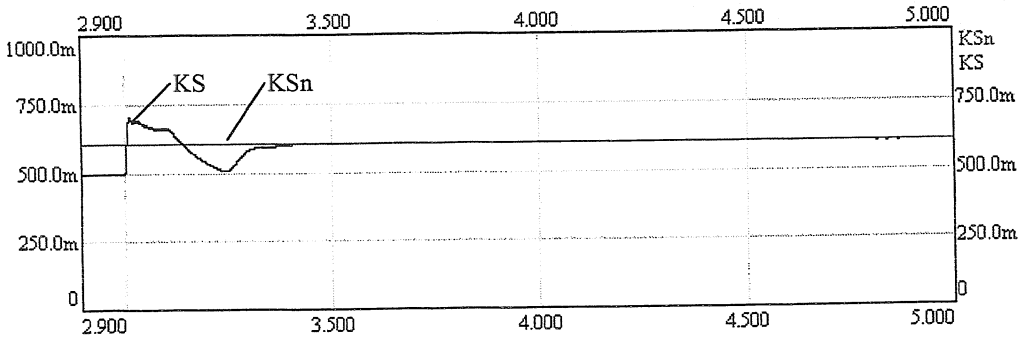
Load power



Voltage



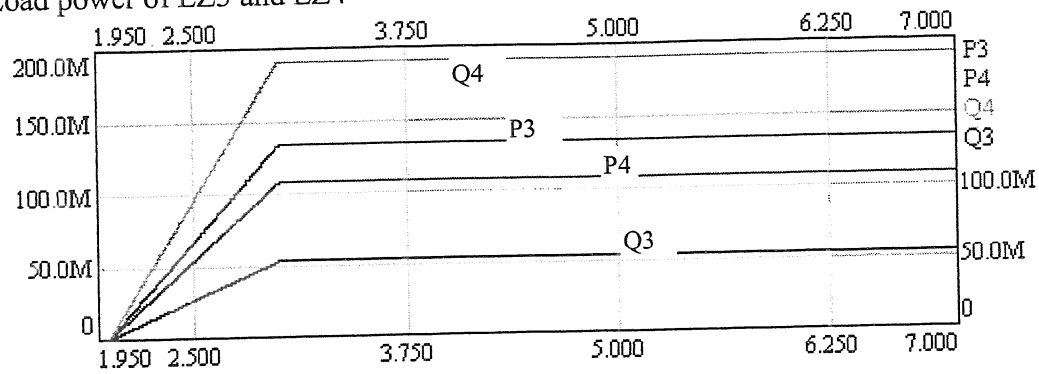
Power-distribution



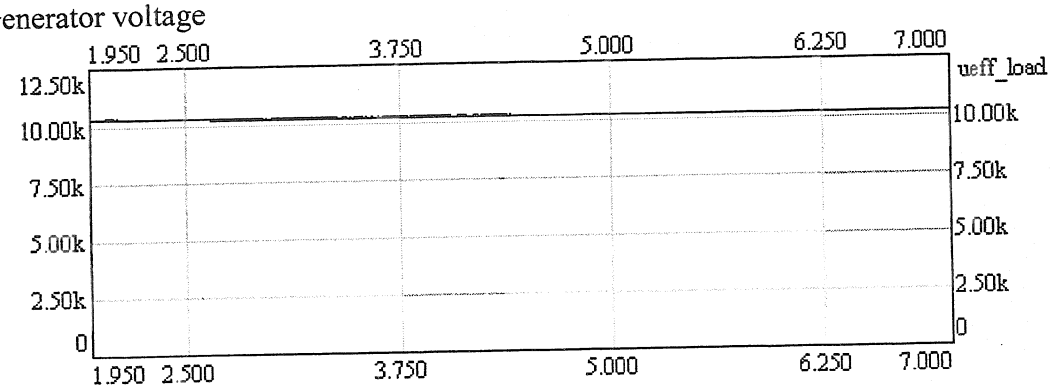
(2) Original parameters

(a) Rising time of step load is 1 second

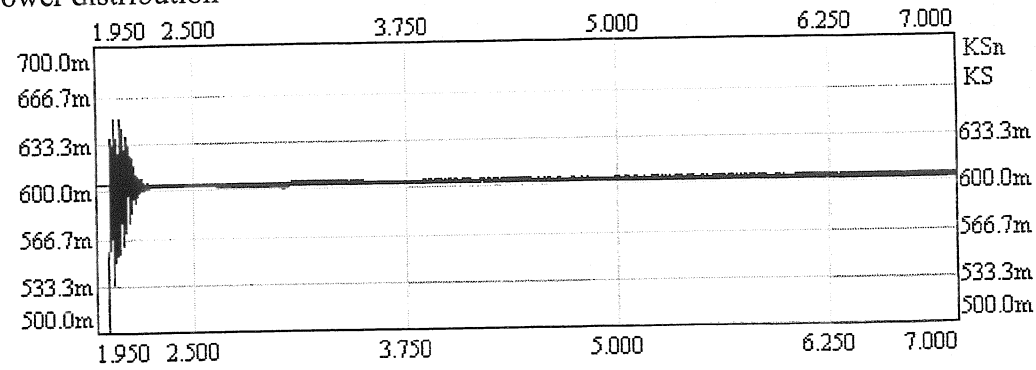
Load power of EZ3 and EZ4



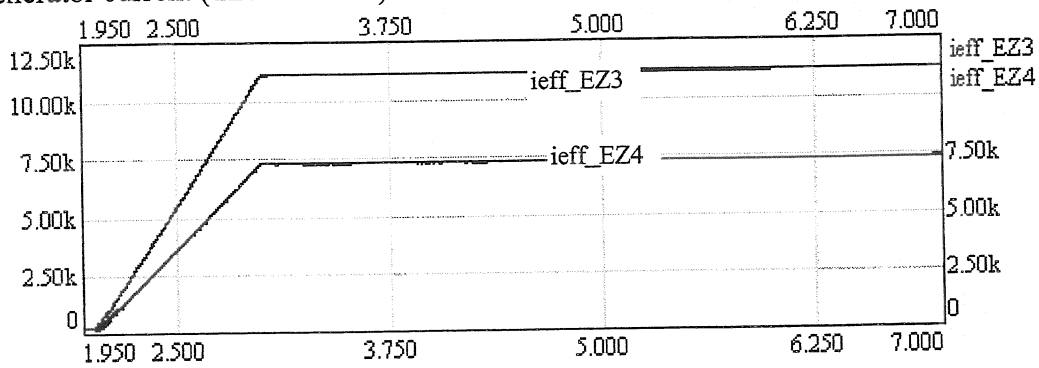
Generator voltage



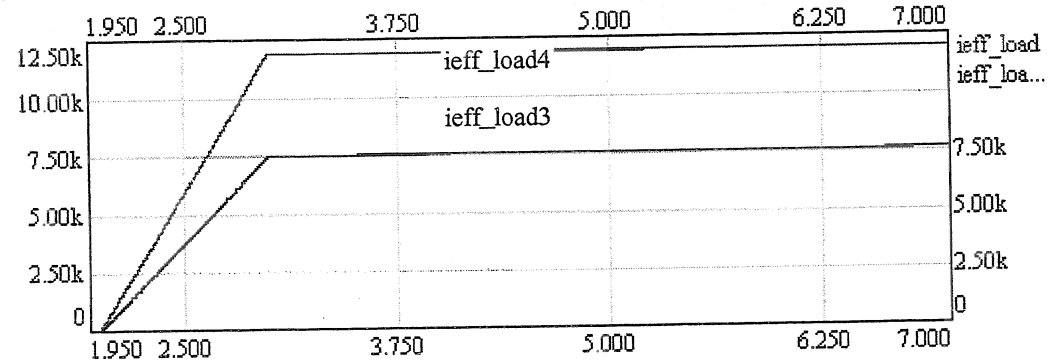
Power distribution



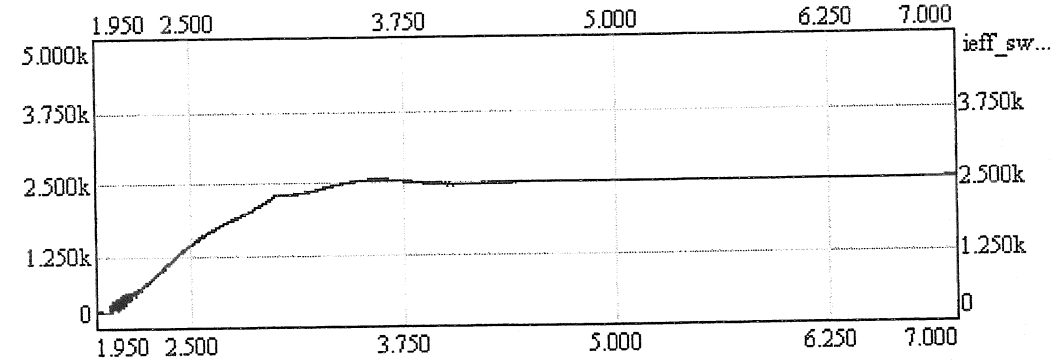
Generator current (EZ3 and EZ4)



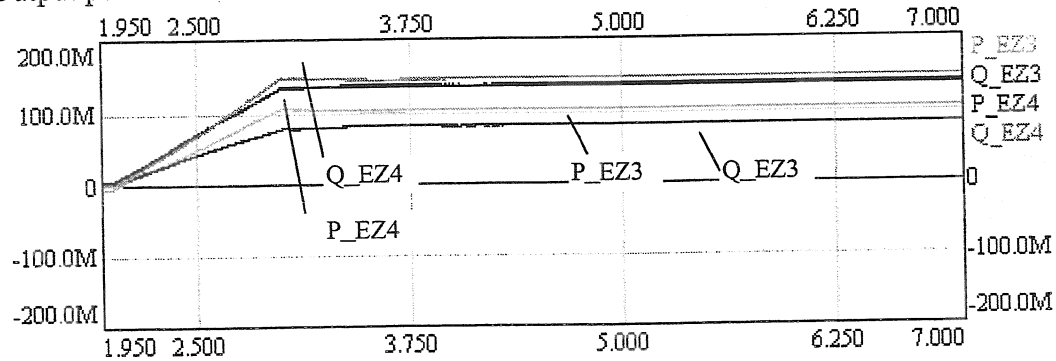
Load current



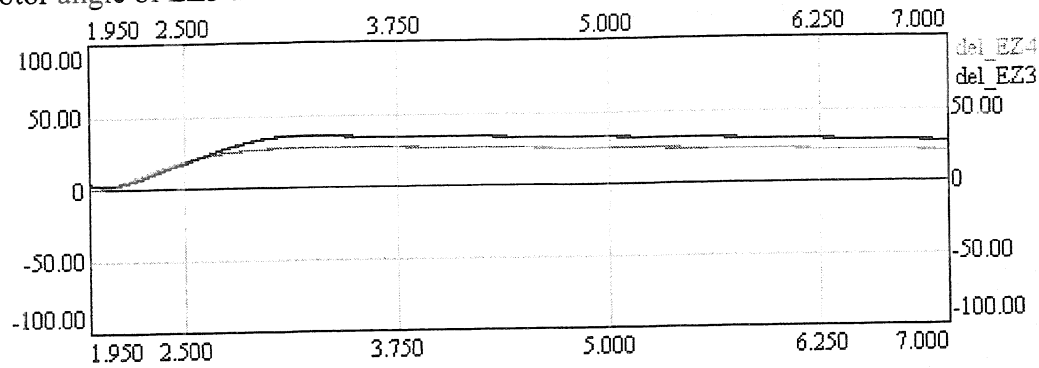
Switch current



Output power of EZ3 and EZ4

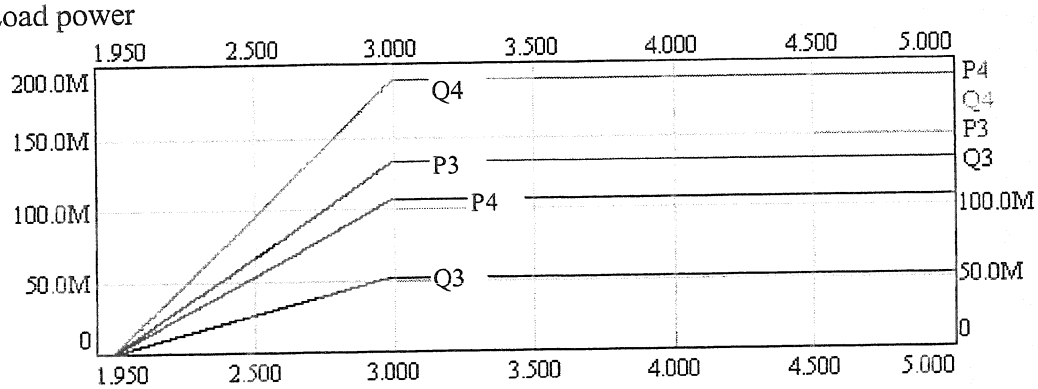


Rotor angle of EZ3 and EZ4

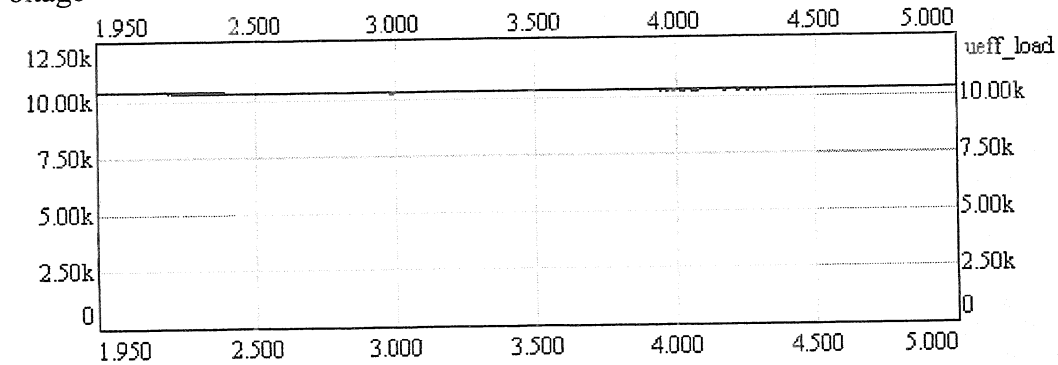


(b) Oscillation when the rising time is 1 second and there is no power distribution controller

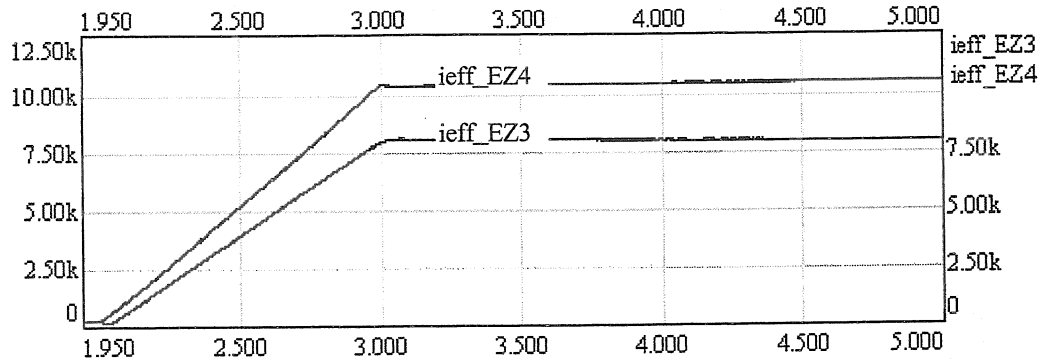
Load power



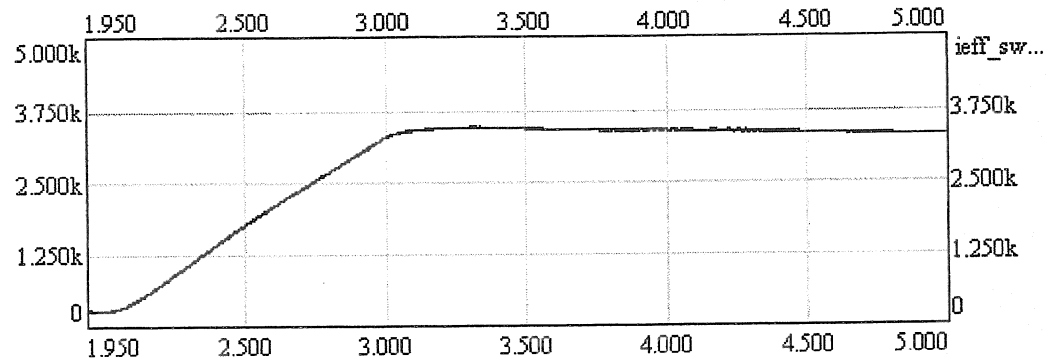
Voltage



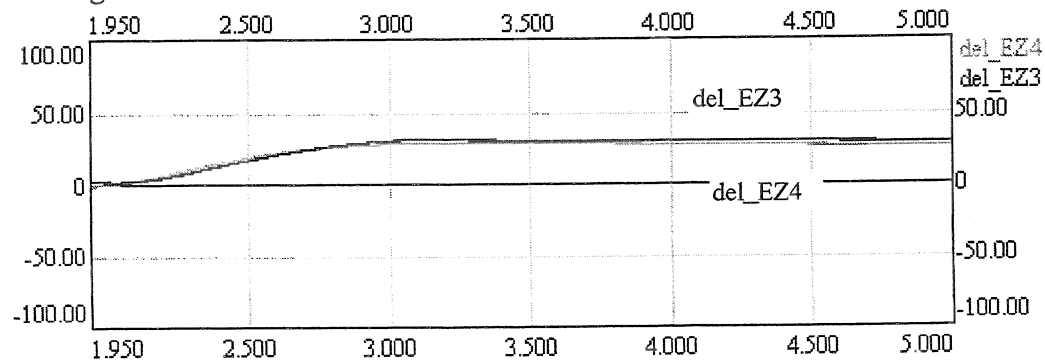
EZ3 and EZ4 current



Switch current



Rotor angle



(c). Open the parallel switch in load

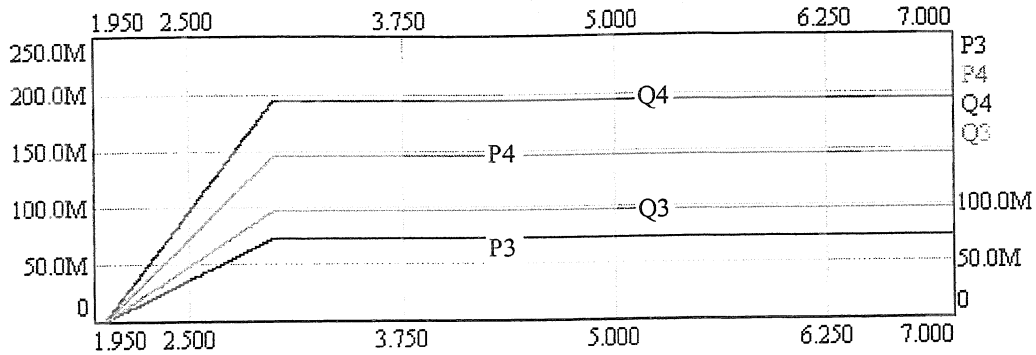
(c1) load3---- Pn_EZ3, cosφ=0.6; load4---- Pn_EZ4, cosq=0.6

(c2) load3---- Pn_EZ3, cosq=0.93; load4----Pn_EZ4, cosq=0.49

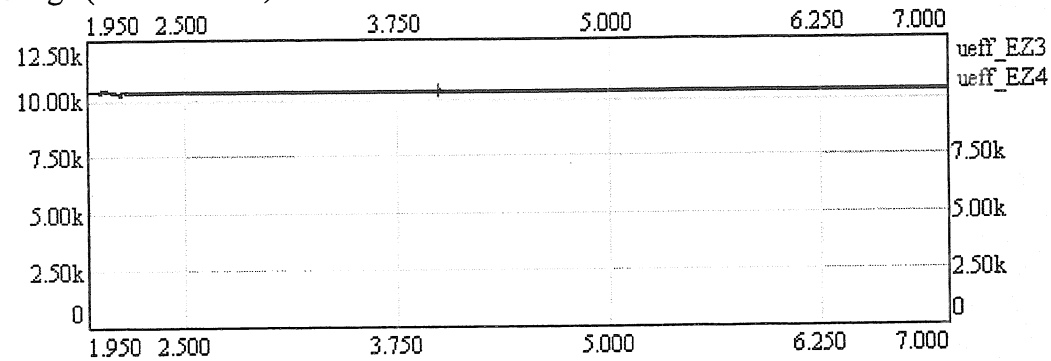
(c) Open the parallel switch in load

(c1) Load3, load4: cosq=0.6

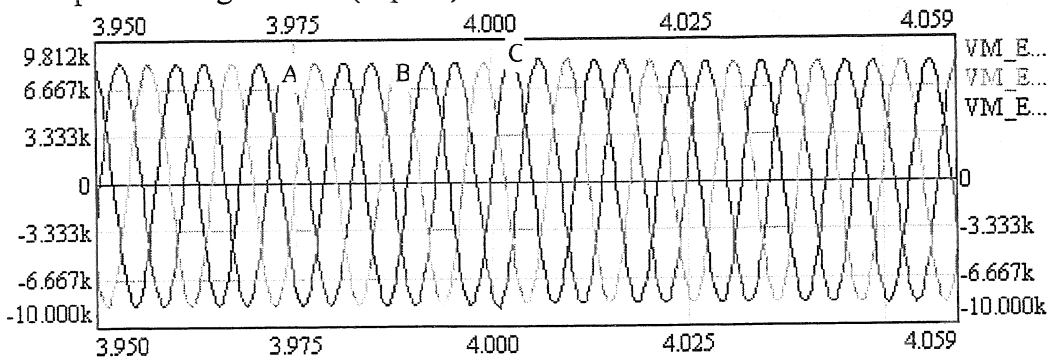
Power



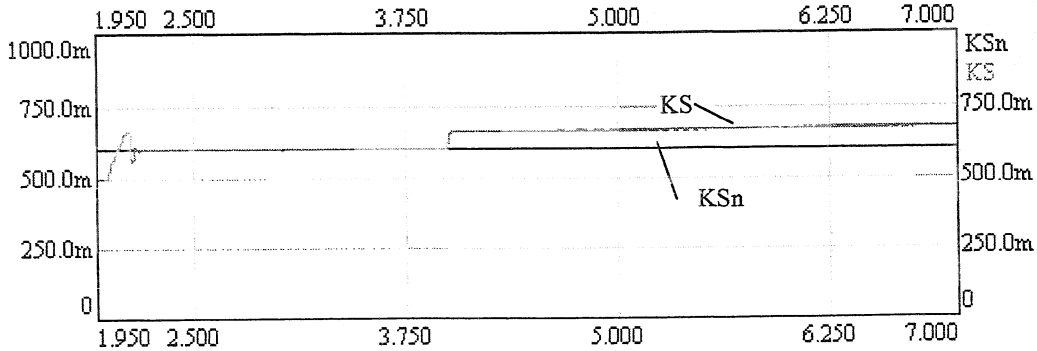
Voltage (EZ3 and EZ4)



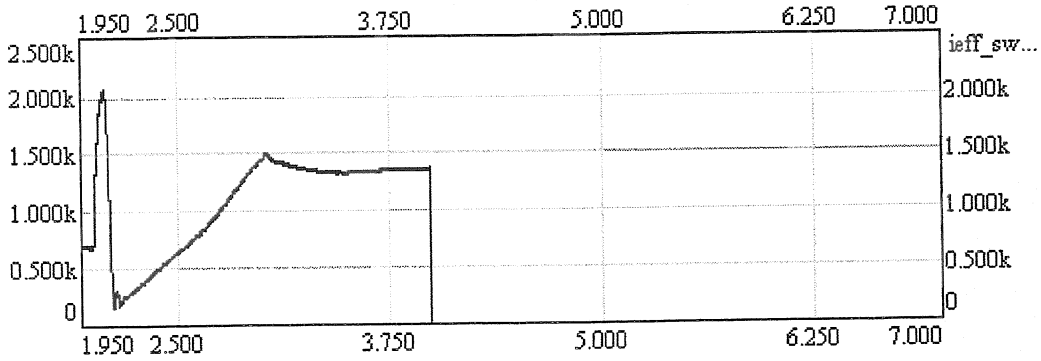
Three phase voltage of EZ3 (expand)



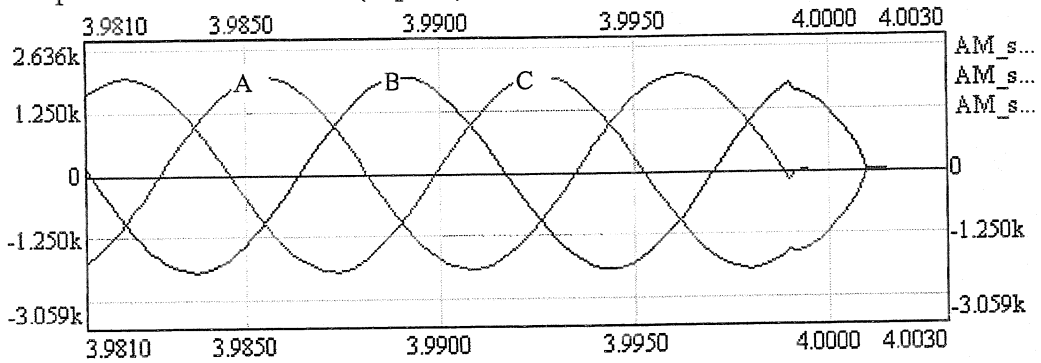
Power distribution



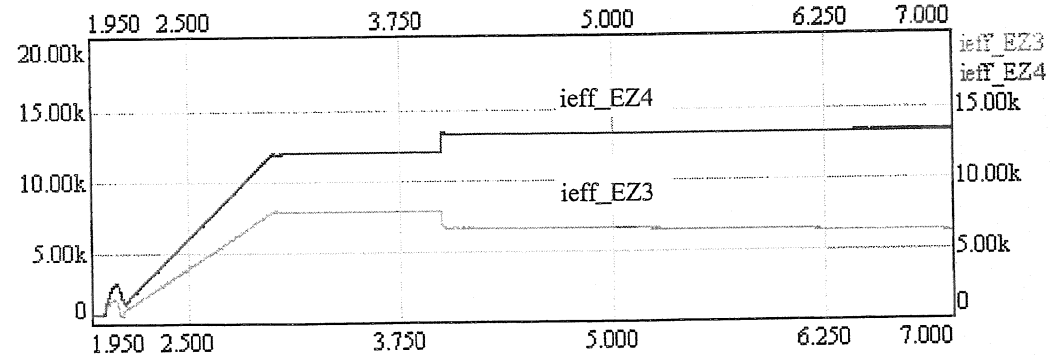
Switch current



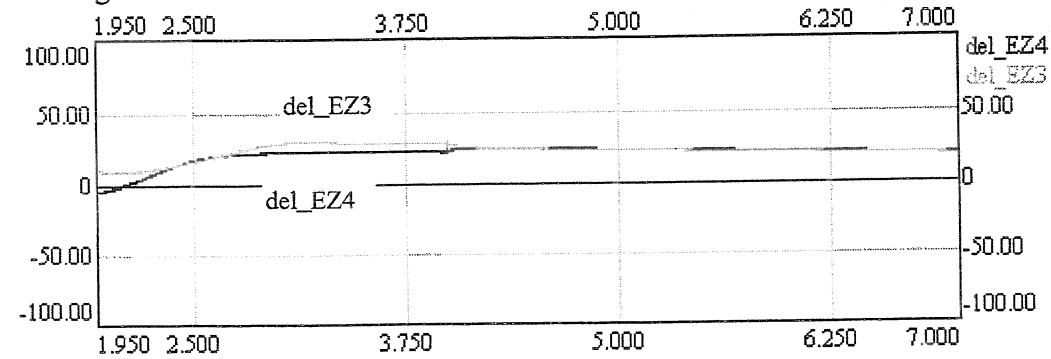
Three phase current of switch (expand)



Generator current

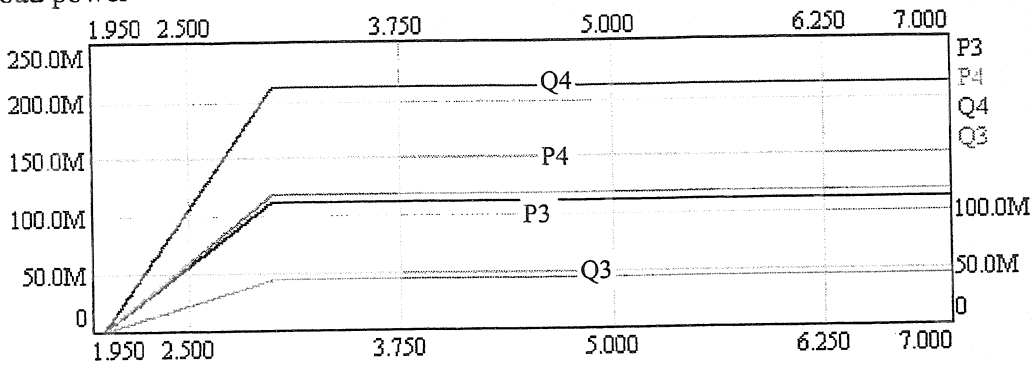


Rotor angle

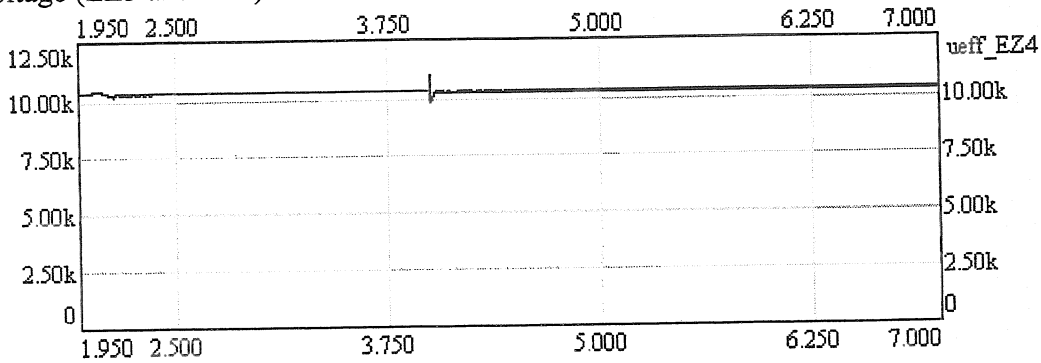


(c2) Load3 , cosq=0.93; load4, cosq=0.49

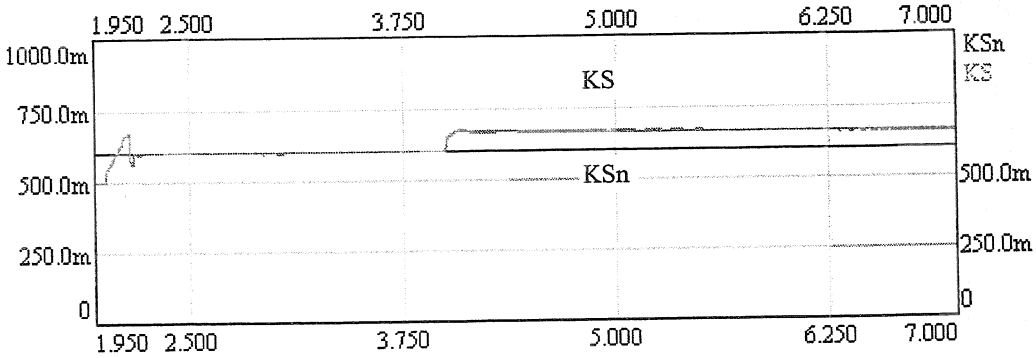
Load power



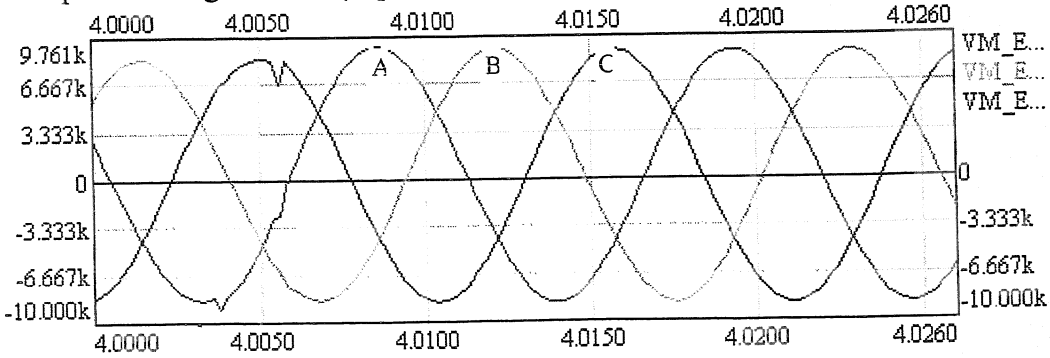
Voltage (EZ3 and EZ4)



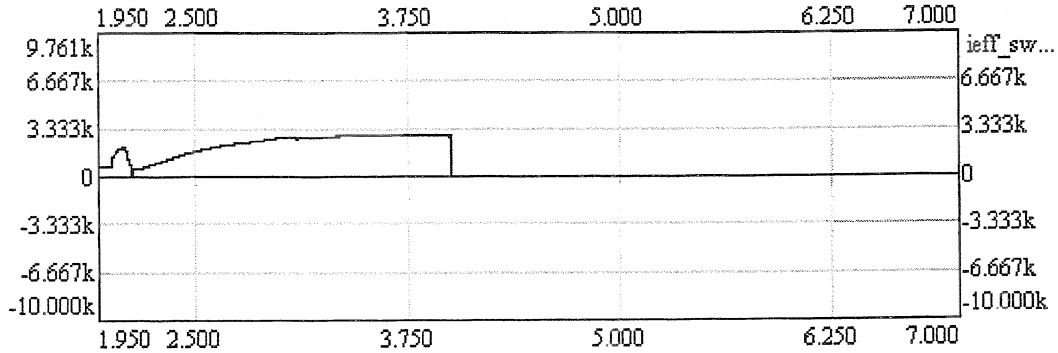
Power distribution



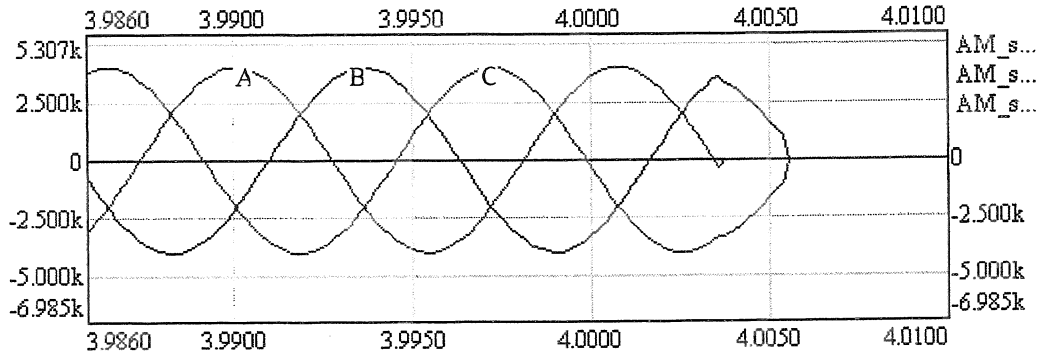
Three phase voltage of EZ3 (expand)



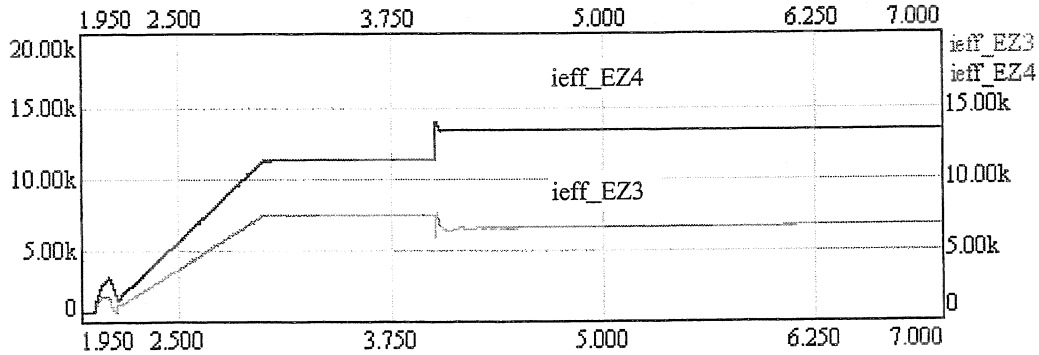
Switch current



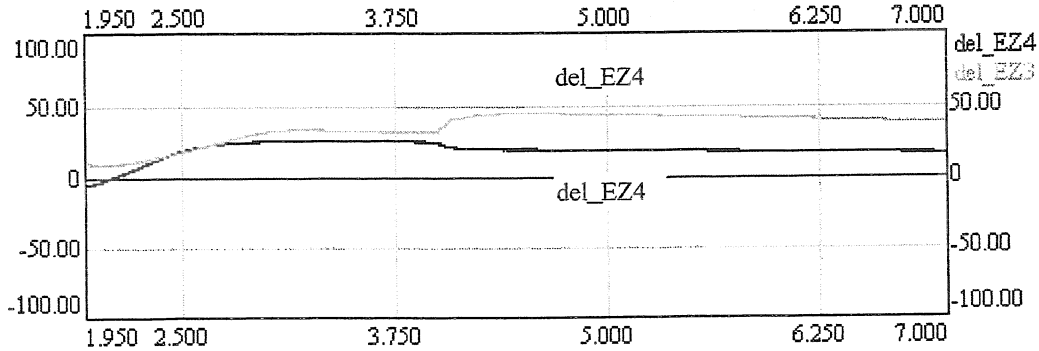
Three phase current of switch(expand)



Generator current

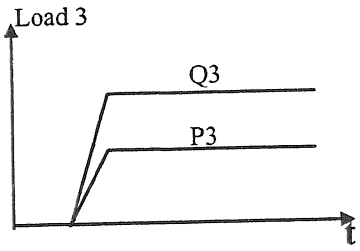


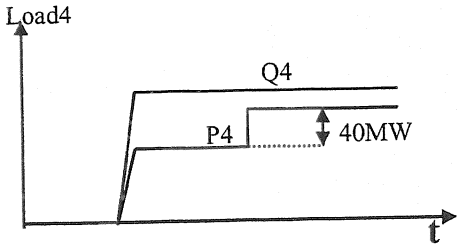
Rotor angle



(d) Behaviour at step function and changing power factor load (P3=P4,Q3=Q4)

(d1) S= 140MVA, cosq=0.8
(d2) S=140MVA, cosq=0.6
(d3) S=140MVA , cosq=0.4
(d4) S=280MVA, cosq=0.8
(d5) S=280MVA, cosq=0.6
(d6) S=280MVA, cosq=0.4
(d7) S=280MVA, cosq=0.8, worst parameters
(d8) S=280MVA, cosq=0.6, worst parameters
(d9) S=280MVA, cosq=0.4, worst parameters, modified condition of control

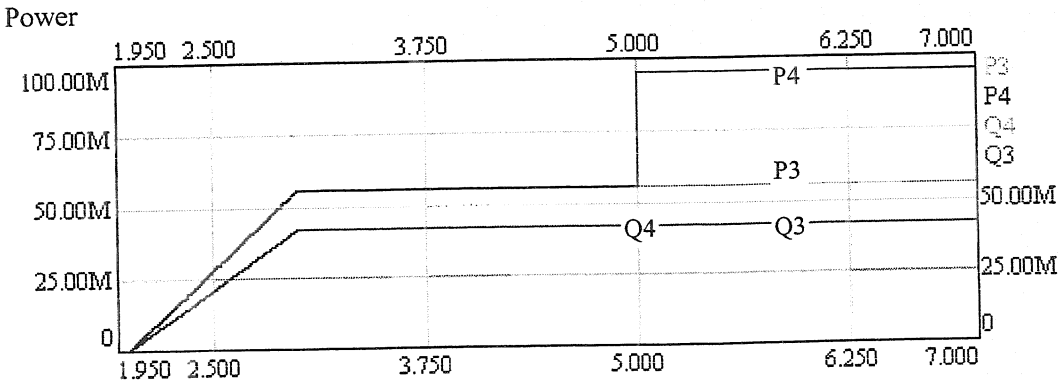




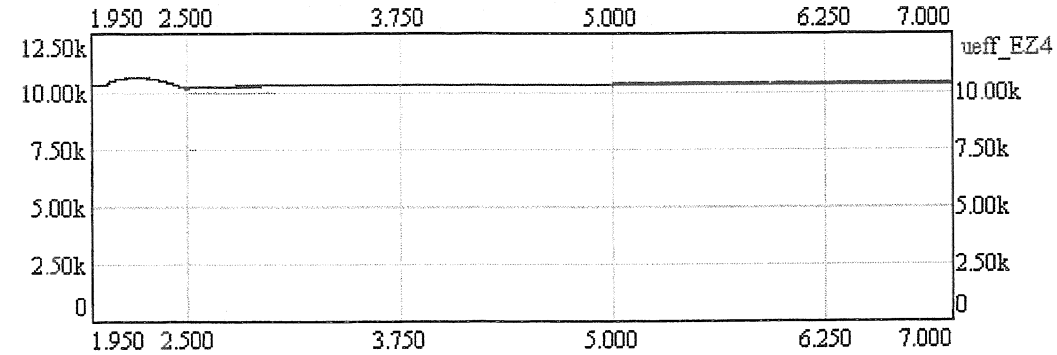
power(MVA)	140			280			280 (worst par.)		
cosφ	0.8	0.6	0.4	0.8	0.6	0.4	0.8	0.6	0.4
switch current (o)	0.863	0.812	0.817	1.707	1.638	1.621	1.722	1.653	1.616
switch current (n)	1.309	1.155	1.197	1.884	1.742	1.777	1.955	1.73	1.796
EZ3 rotor angle (o)	28.31	20.29	13.28	36.67	25.36	17.48	34.76	25.89	17.63
EZ3 rotor angle (n)	36.60	27.75	20.90	41.41	30.46	22.39	39.09	30.30	22.39
EZ4 rotor angle (o)	21.41	15.18	10.32	27.10	20.25	13.85	24.81	19.39	13.50
EZ4 rotor angle (n)	24.17	21.07	16.25	30.30	23.39	17.99	28.27	23.55	17.63

Note: current unit is kA; angle unit is deg. ; o-- before step power; n--after step power, read: maximum of angle.

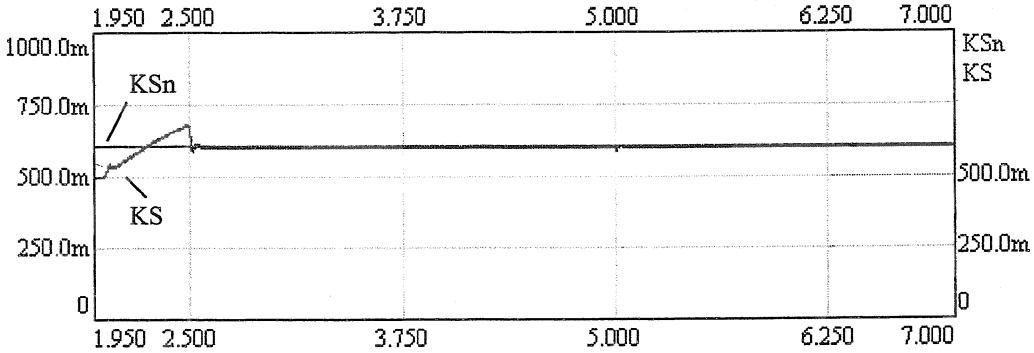
(d) Behaviour at step function and changing power factor load
(d1) S= 140MVA, cosq=0.8



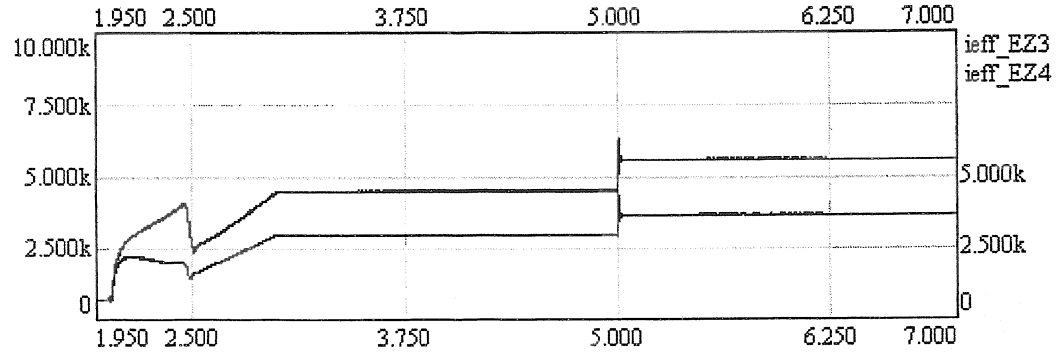
Bus voltage



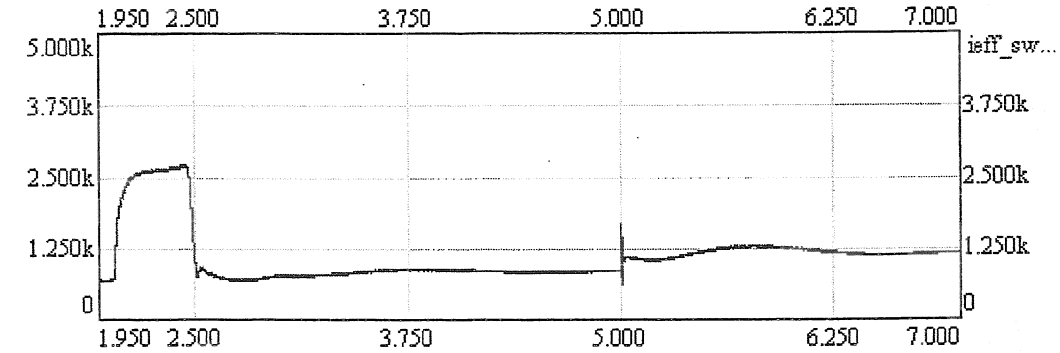
Power distribuation



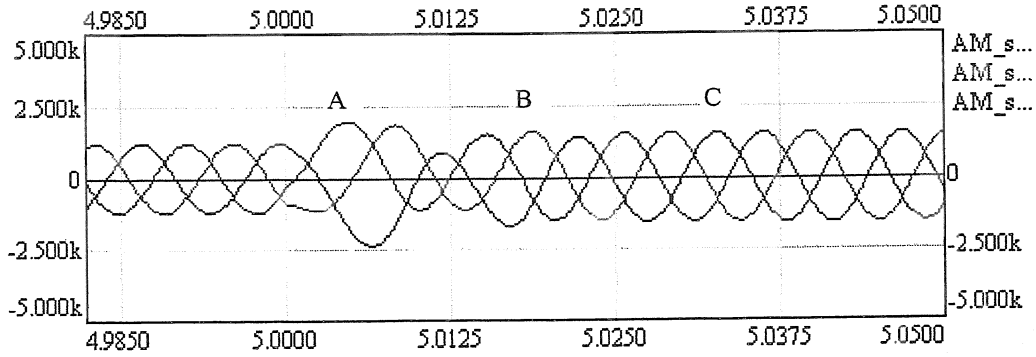
Generator current



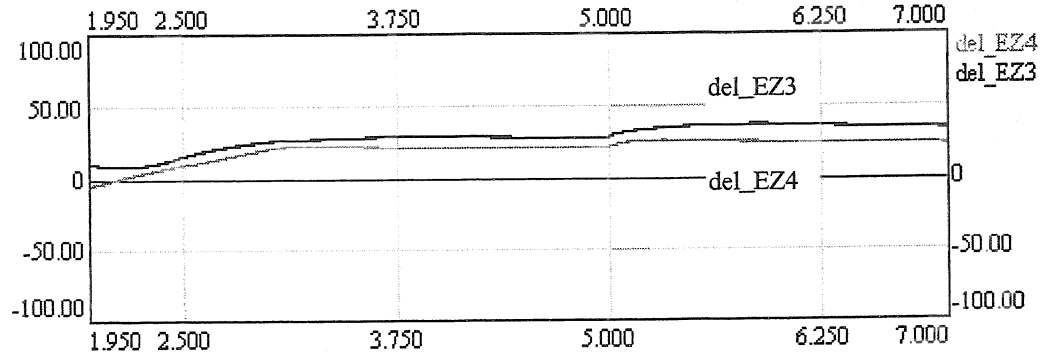
switch current



Three phase current of switch

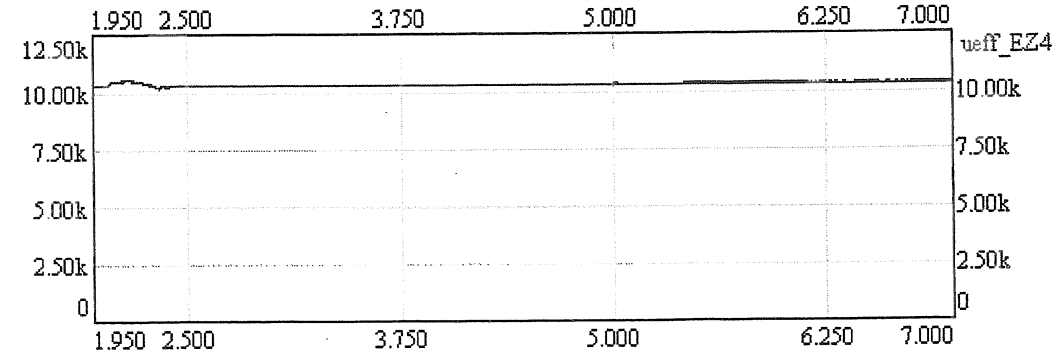


Rotor angle

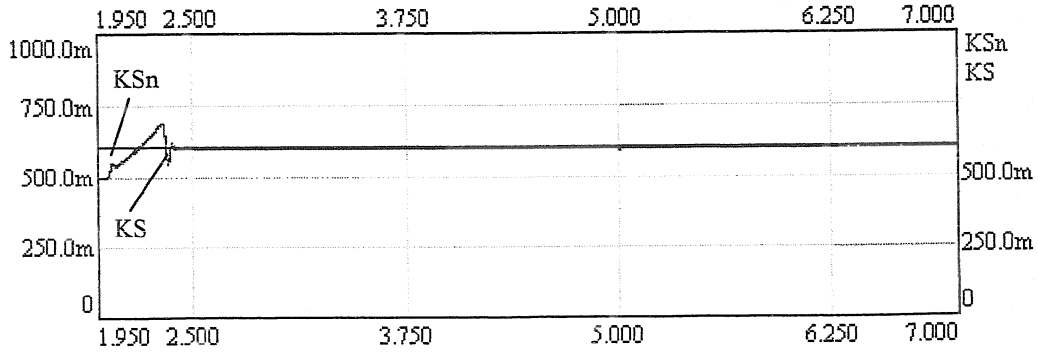


(d2) S=140MVA, cosq=0.6

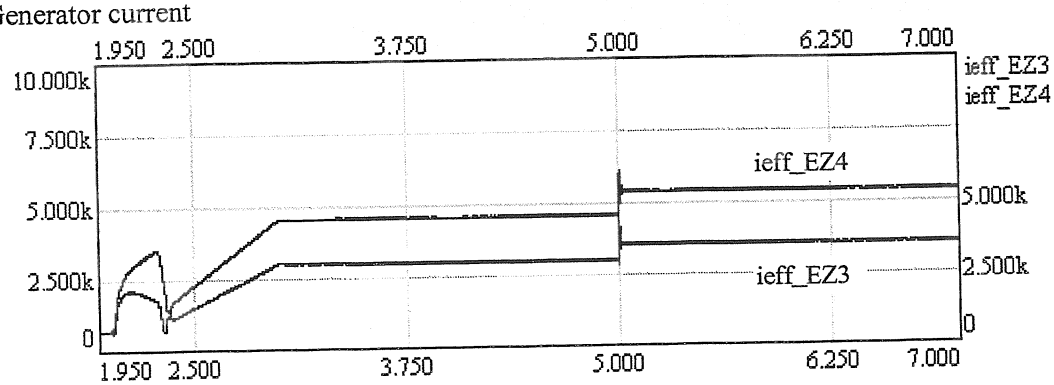
Bus voltage



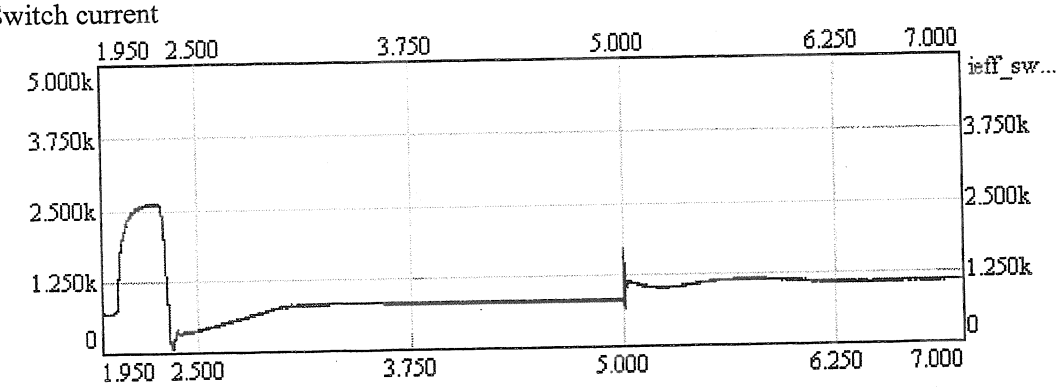
Power distribuation



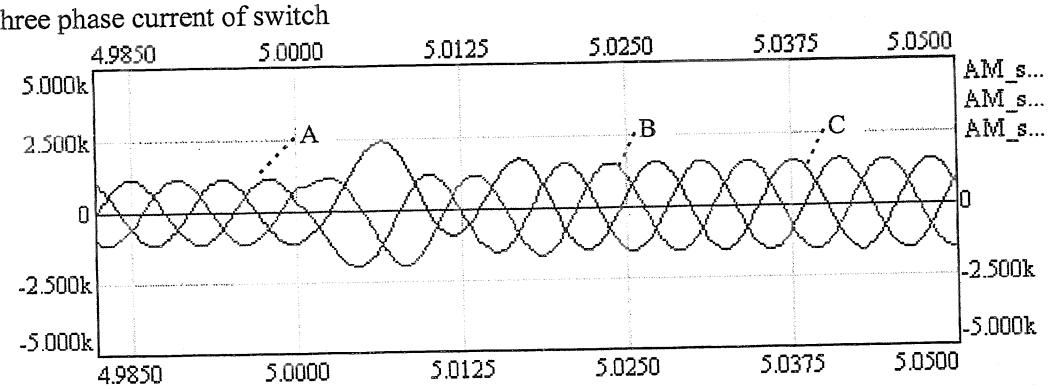
Generator current



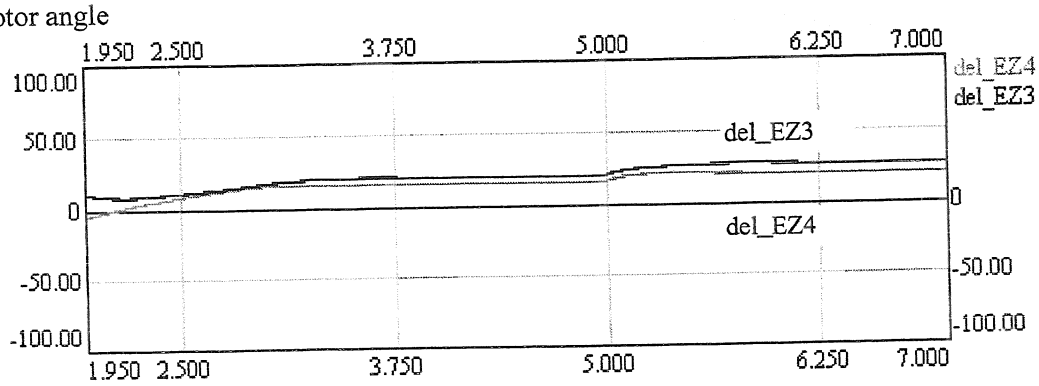
Switch current



Three phase current of switch

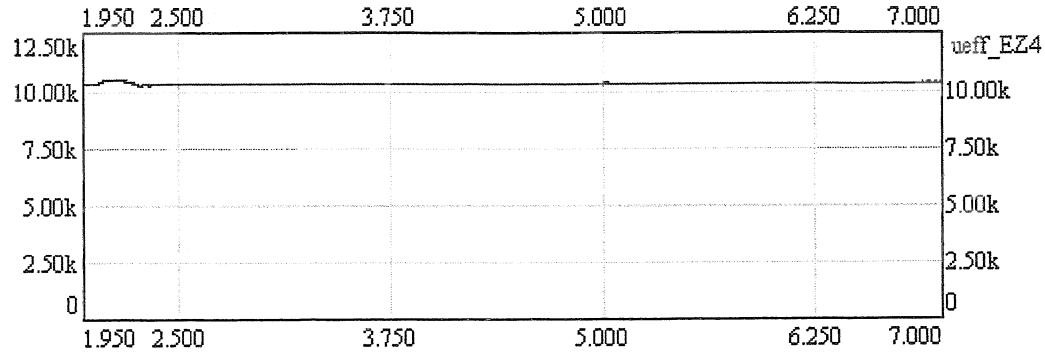


Rotor angle

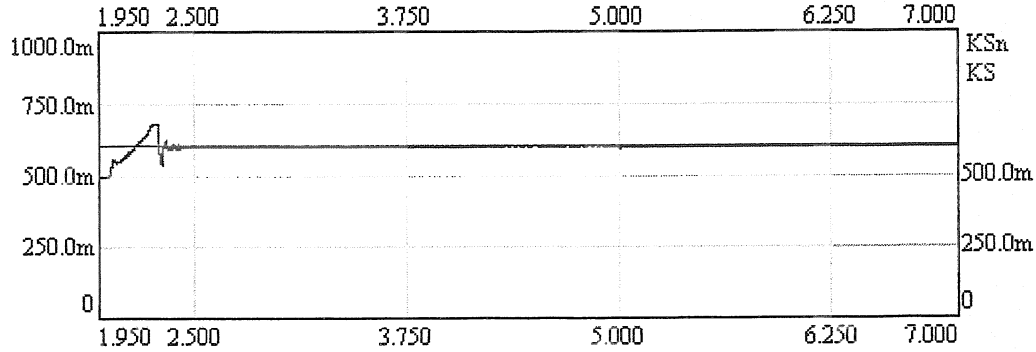


(d3) S=140MVA , cosq=0.4

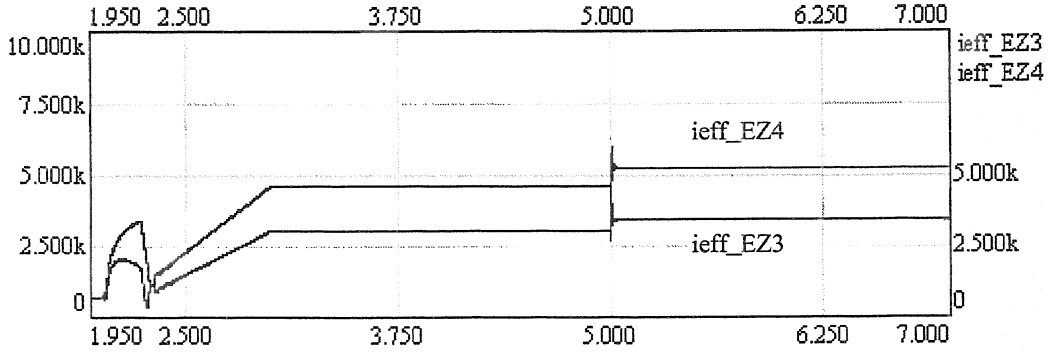
Bus voltage



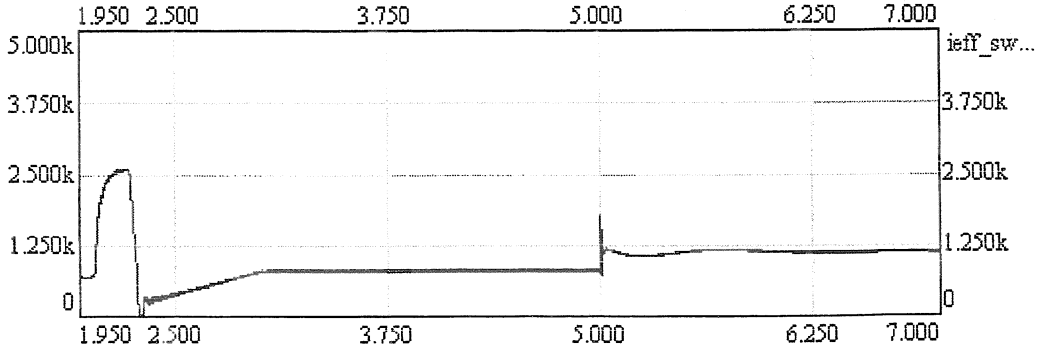
Power distribuation



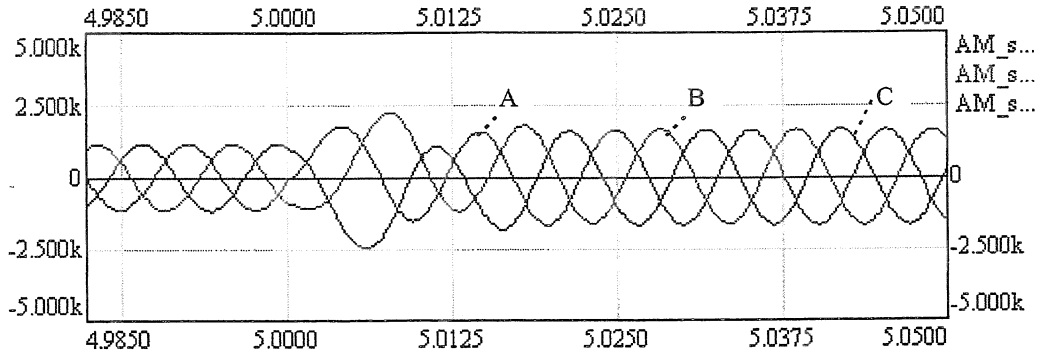
Generator current



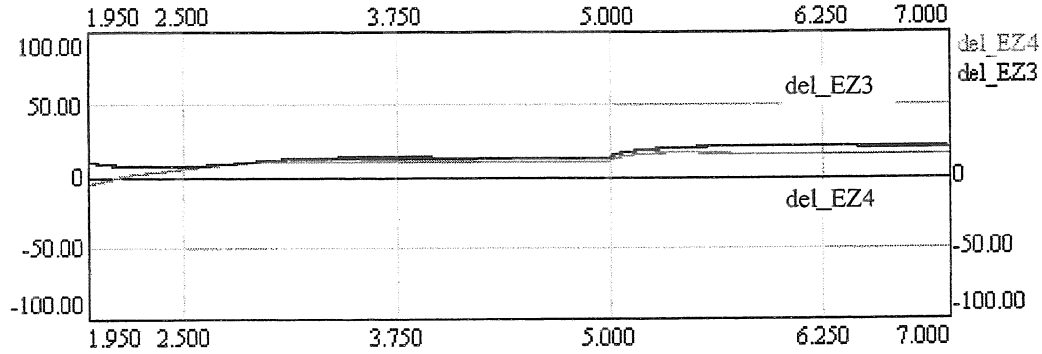
Switch current



Three phase current of switch

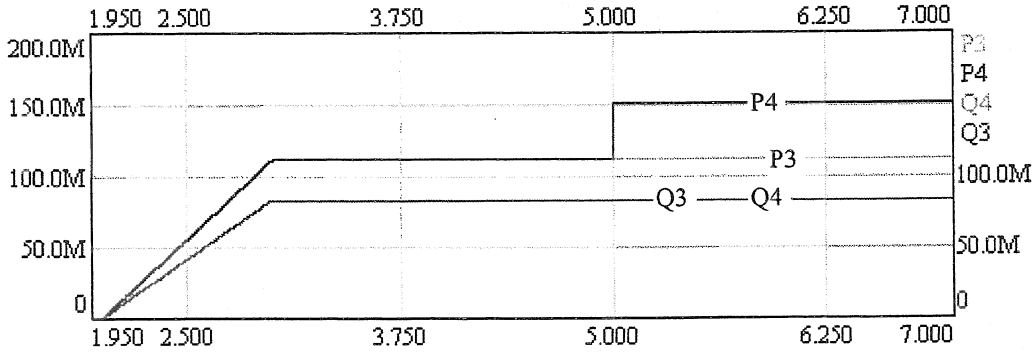


Rotor angle

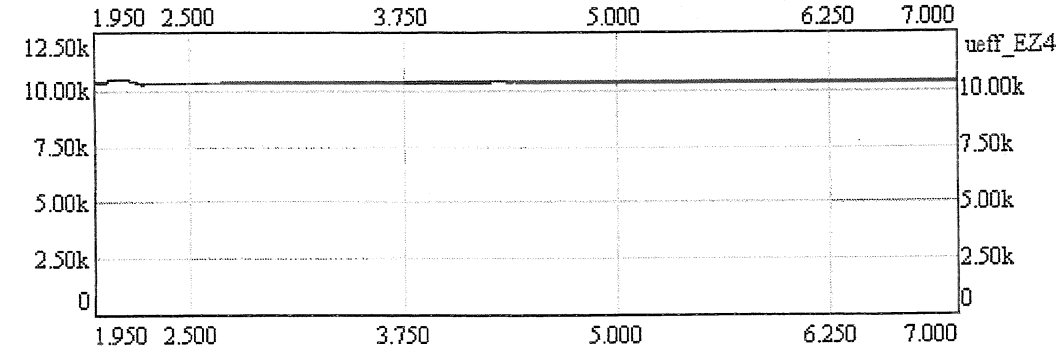


(d4) S=280MVA, cos q=0.8

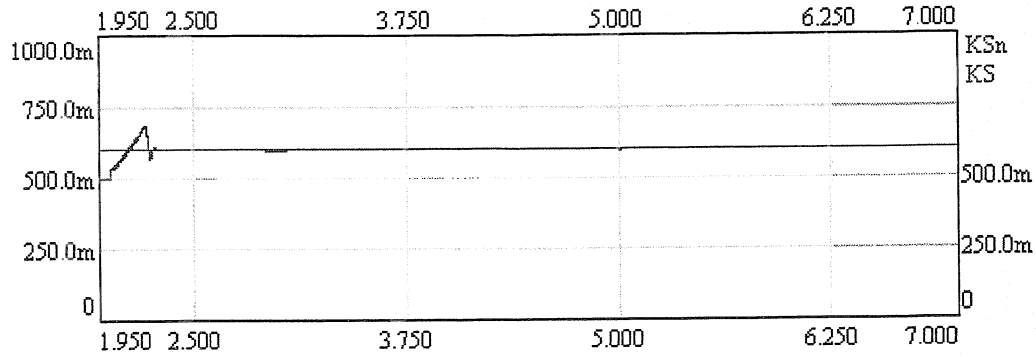
Power



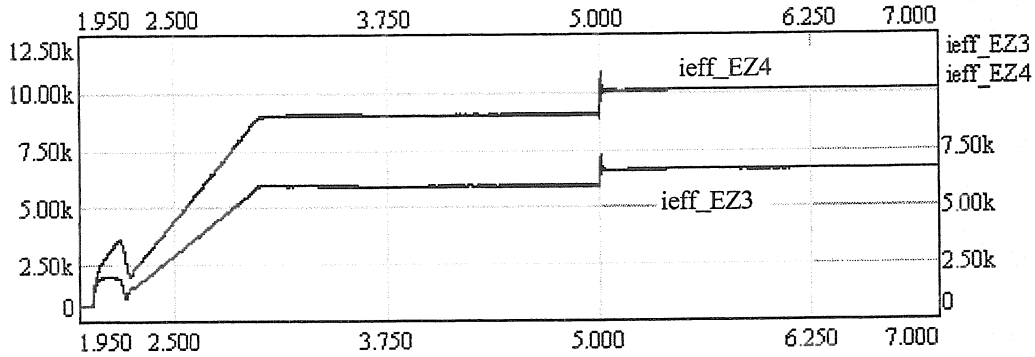
Bus voltage



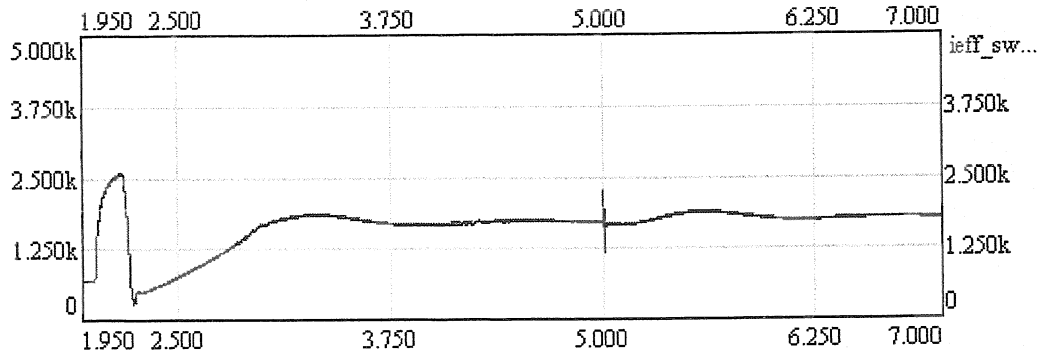
Power distribuation



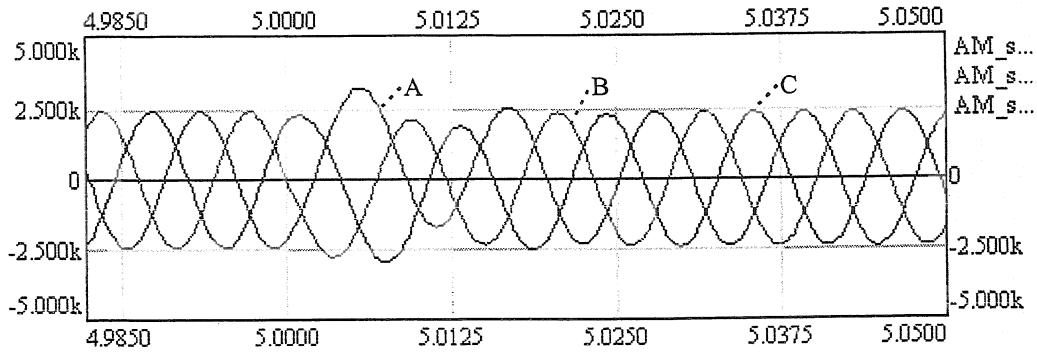
Generator current



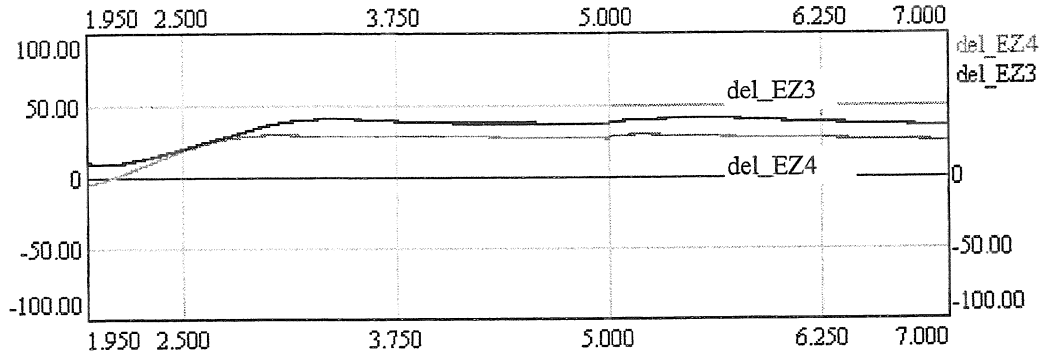
Switch current



Three current of switch

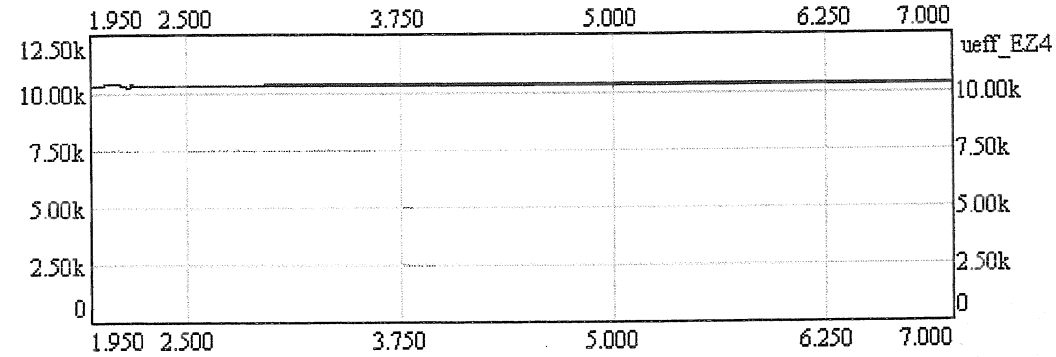


Rotor angle

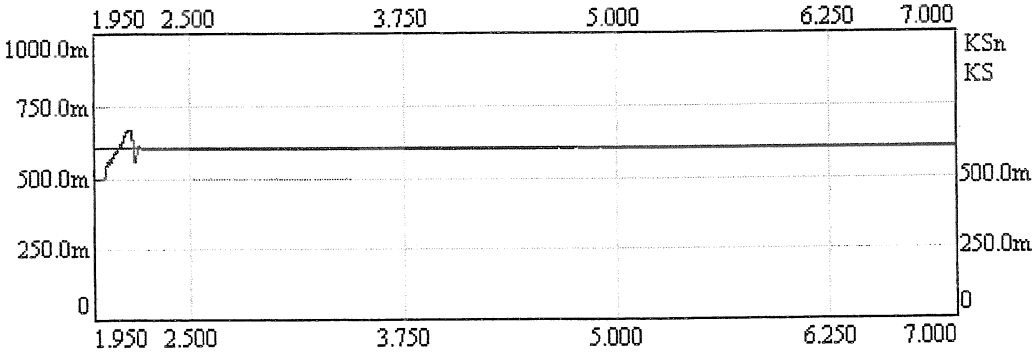


(d5) S=280MVA, cosq=0.6

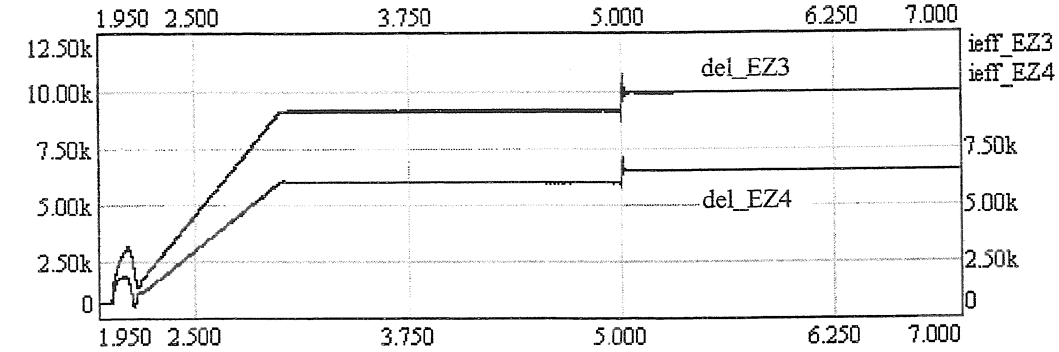
Bus voltage



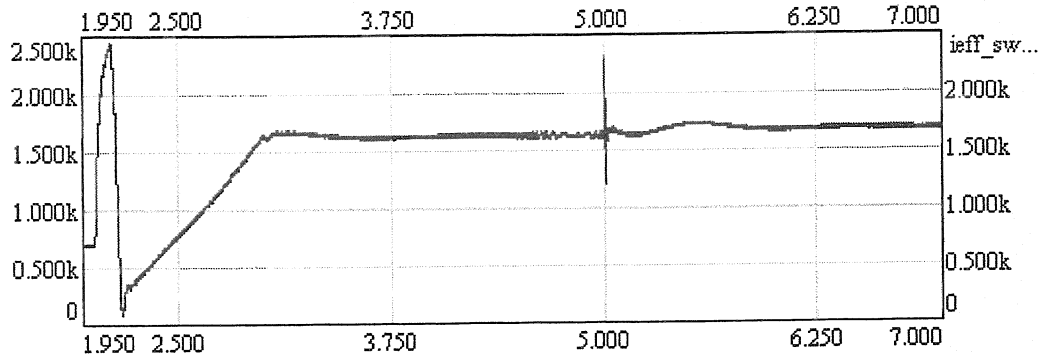
Power distribuation



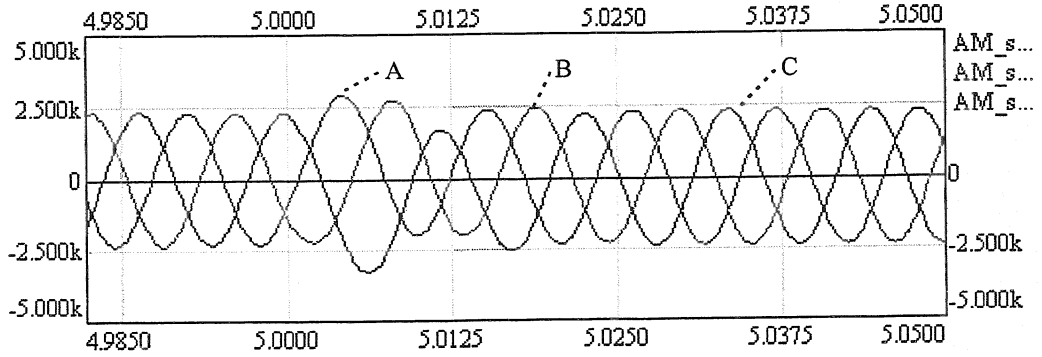
Generator current



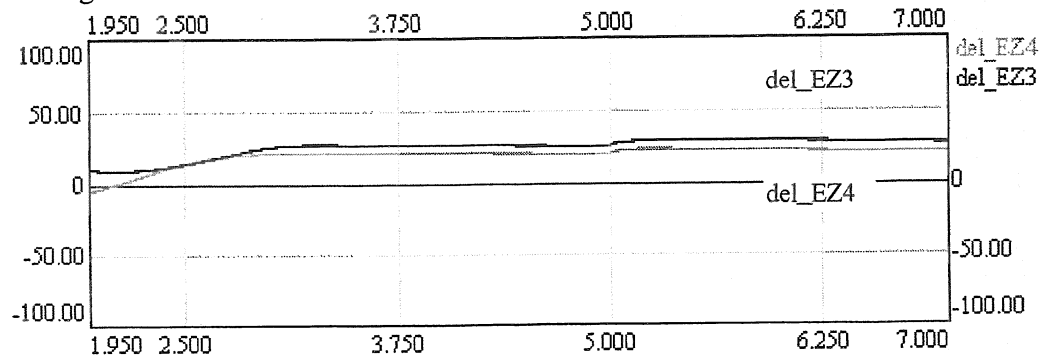
Switch current



Three phase current of switch

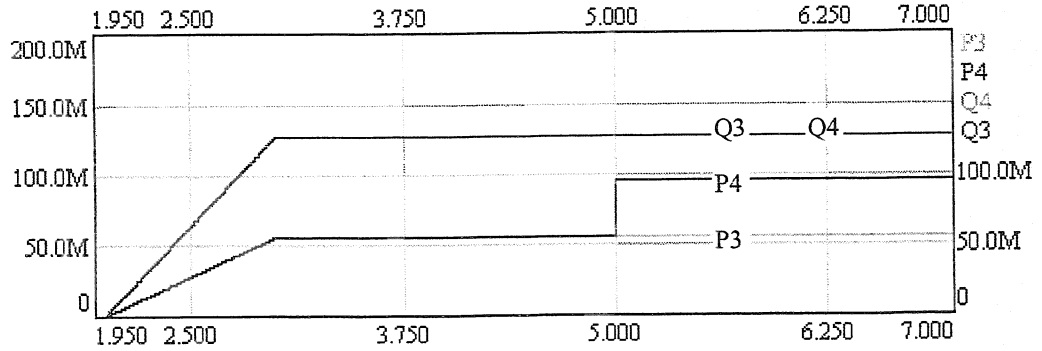


Rotor angle

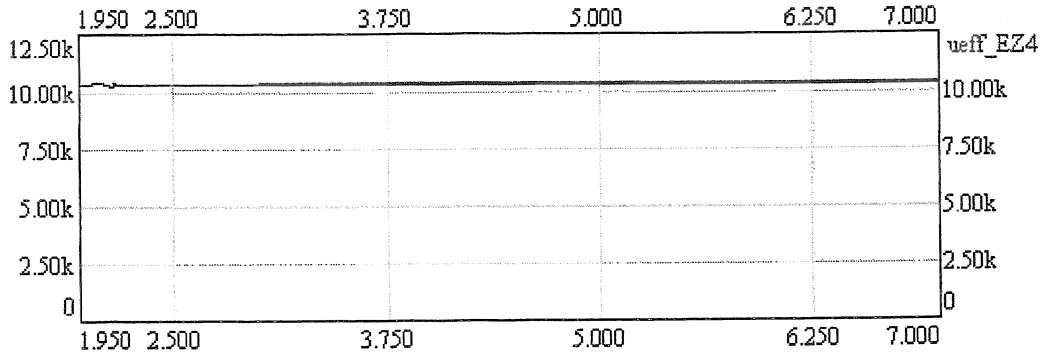


(d6) S=280MVA, cosq=0.4

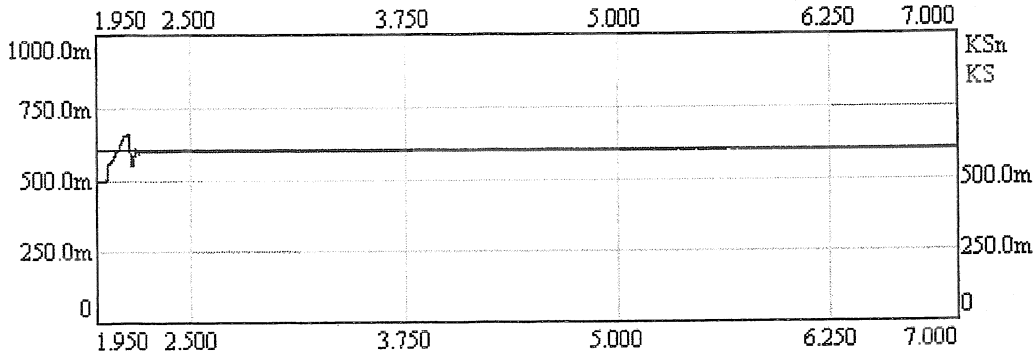
Power



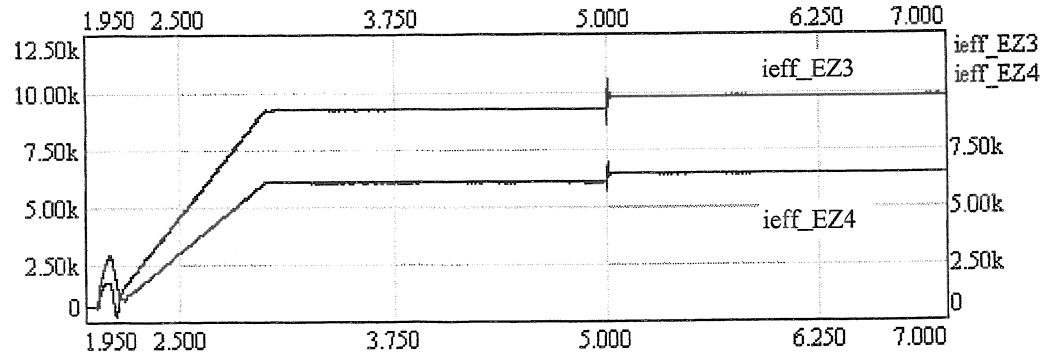
Bus voltage



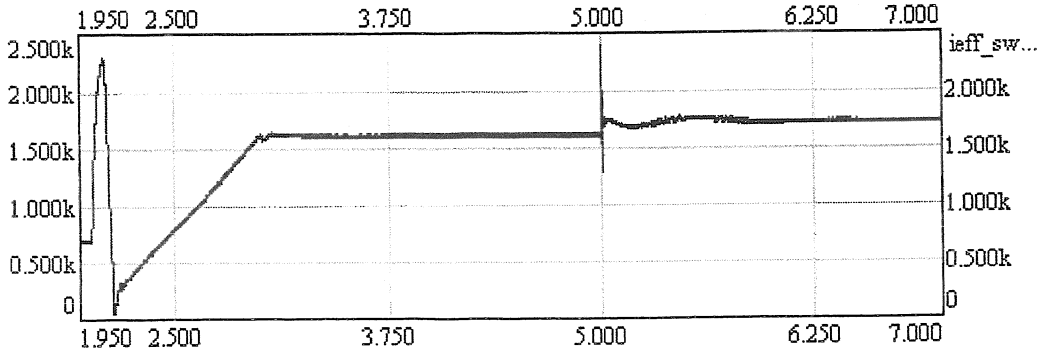
Power distribuation



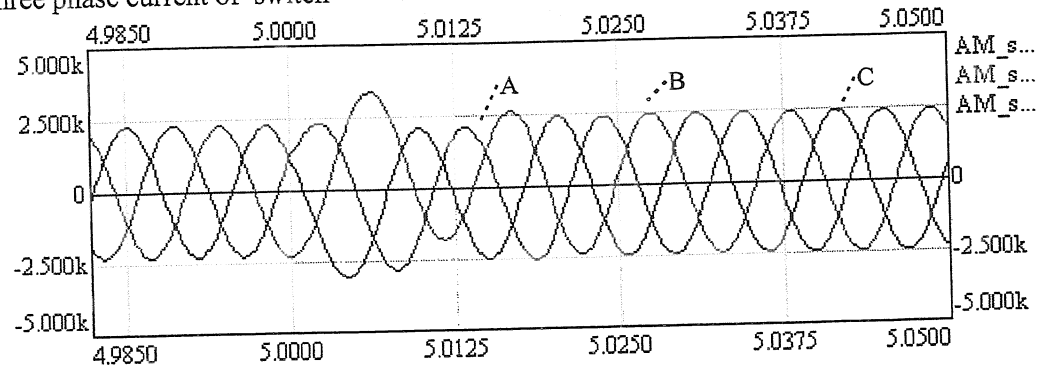
Generator current



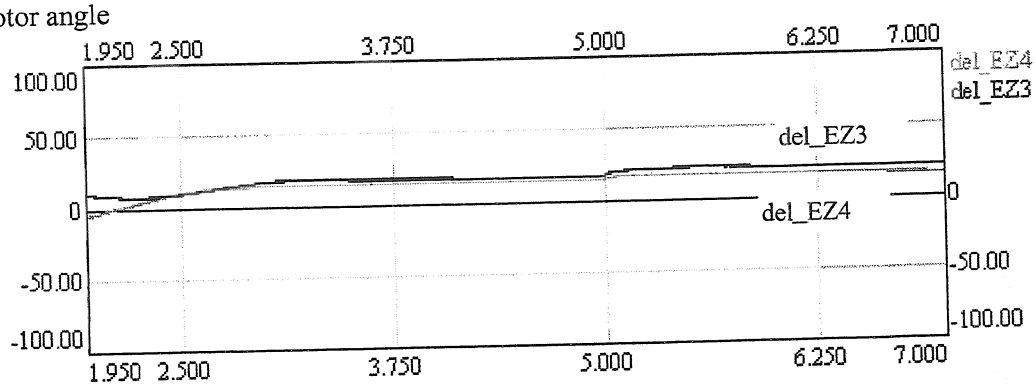
Switch current



Three phase current of switch

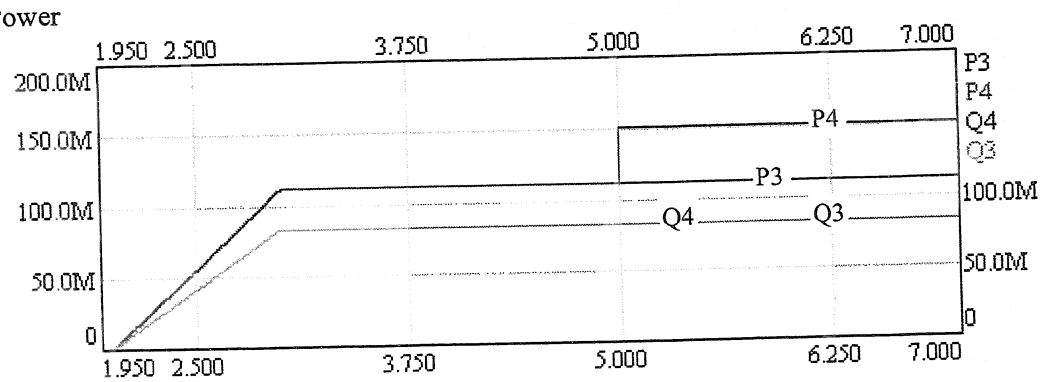


Rotor angle

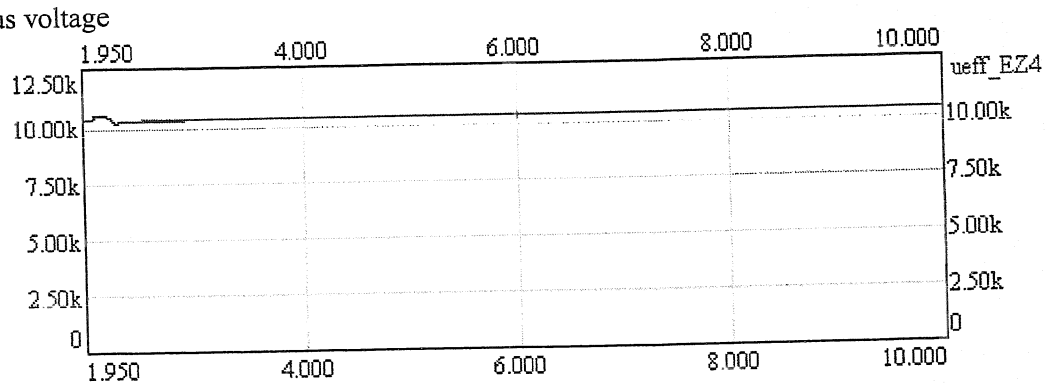


(d7) S=280MVA, cos q=0.8 (worse parameter of generator)

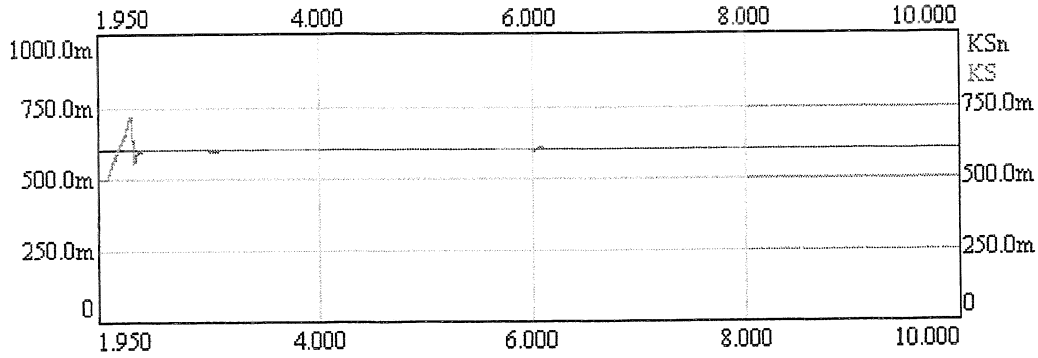
Power



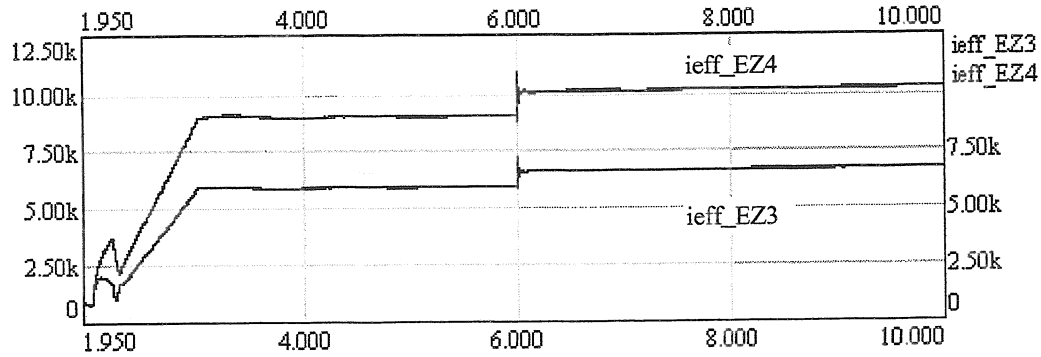
Bus voltage



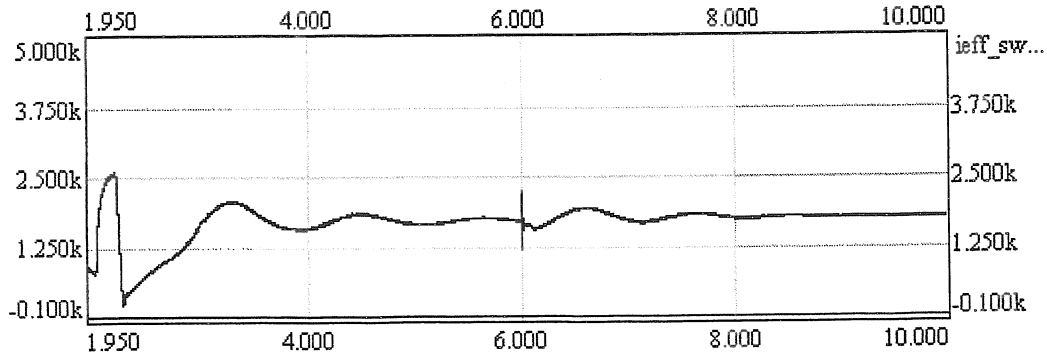
Power distribuation



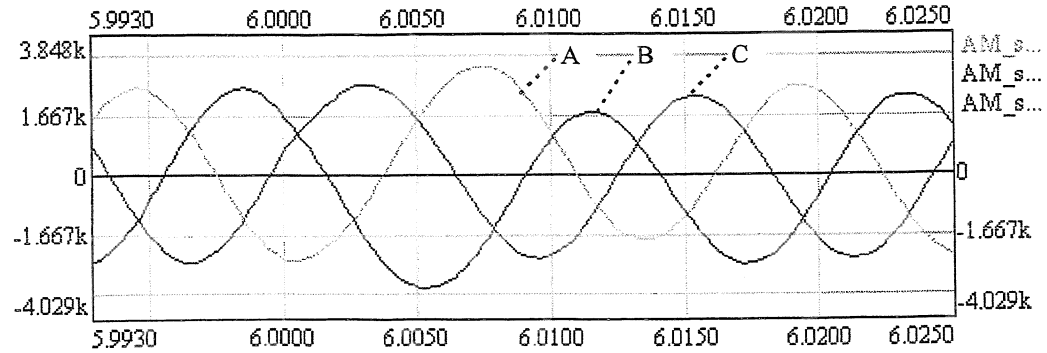
Generator current



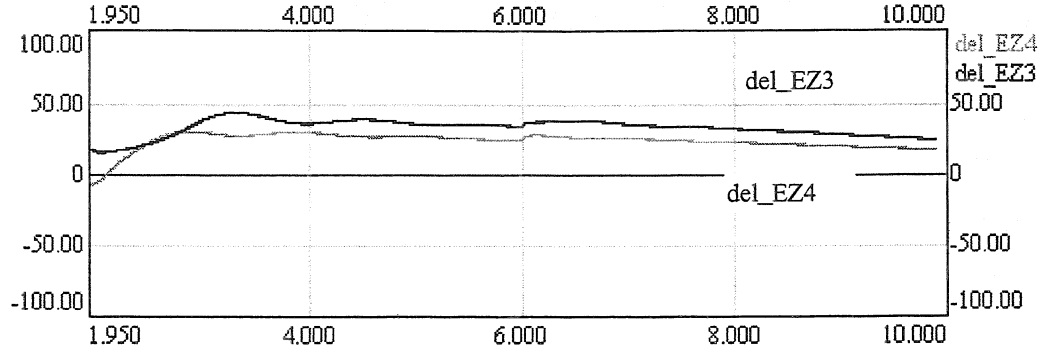
Switch current



Three phase current of switch

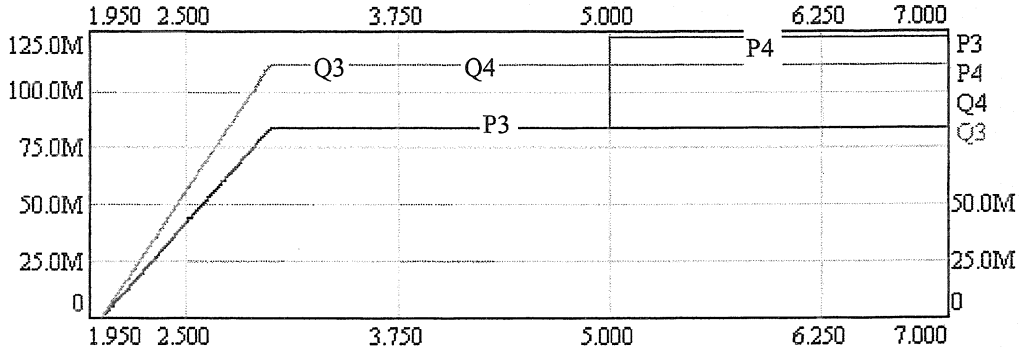


Rotor angle

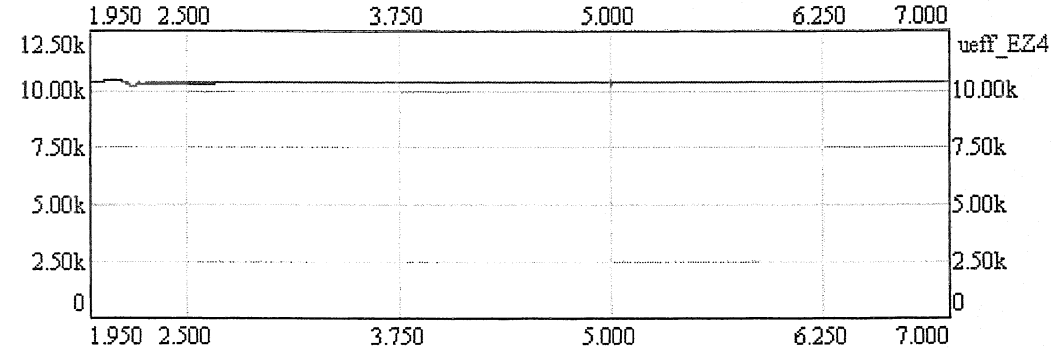


(d8) S=280MVA, cosq=0.6 (worse parameter of generator)

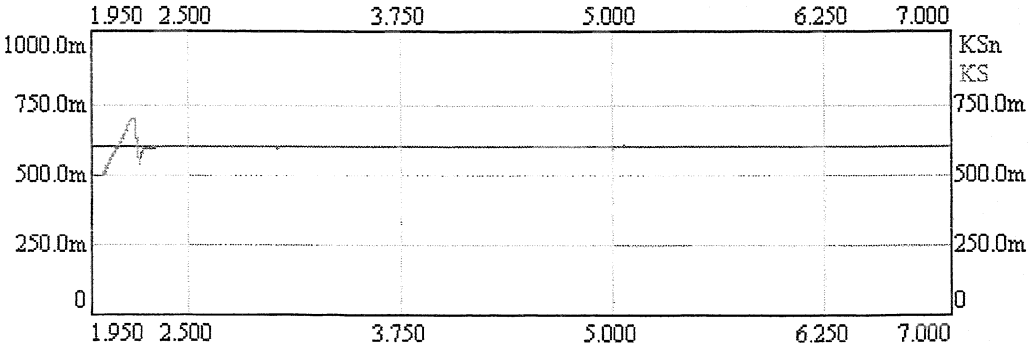
Power



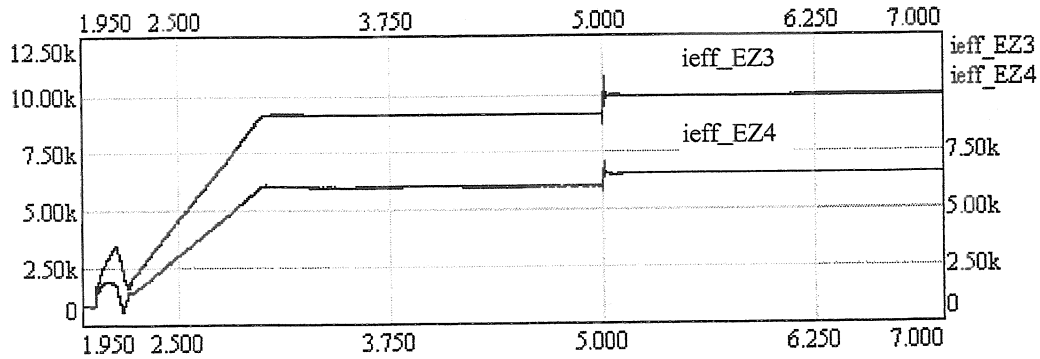
Bus voltage



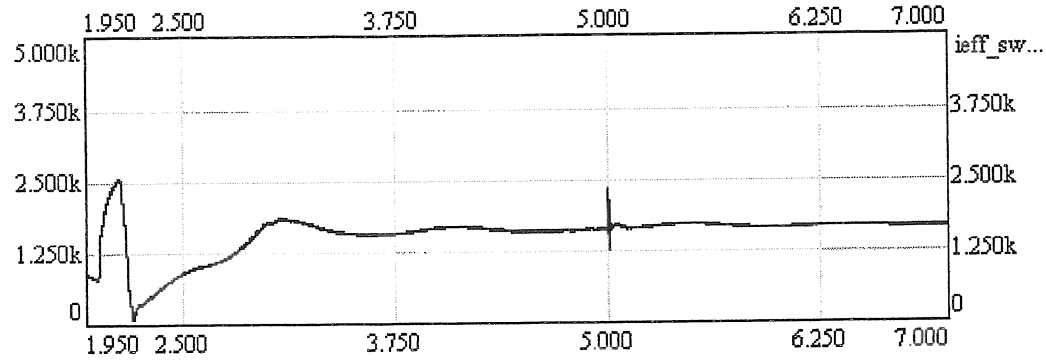
Power distribuation



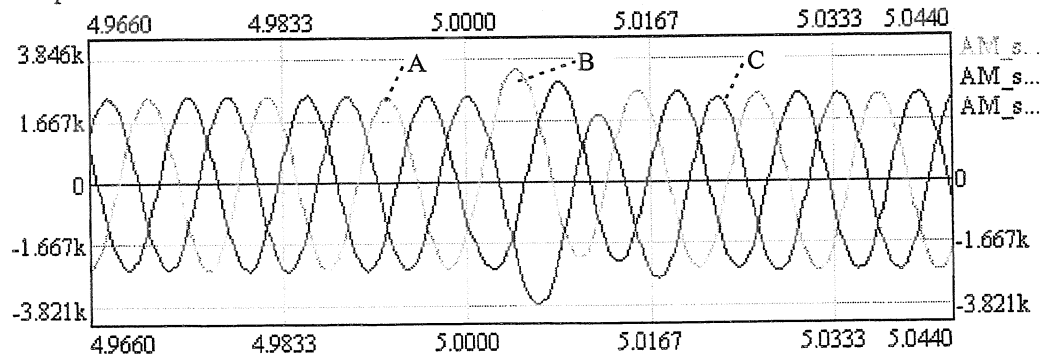
Generator current



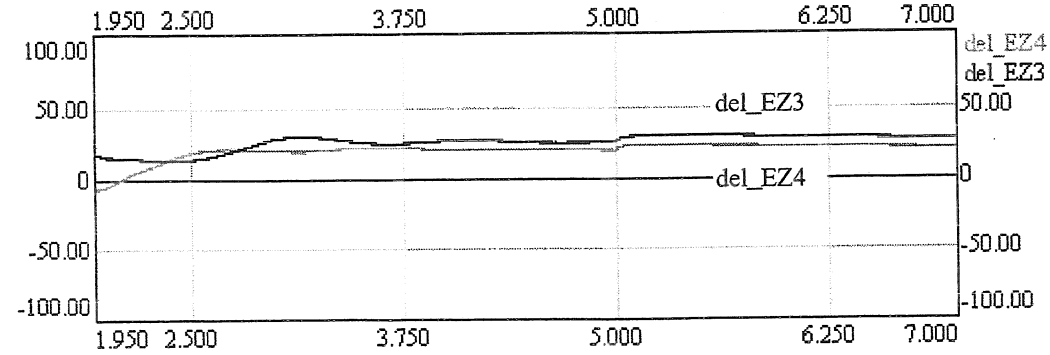
Switch current



Three phase current of switch

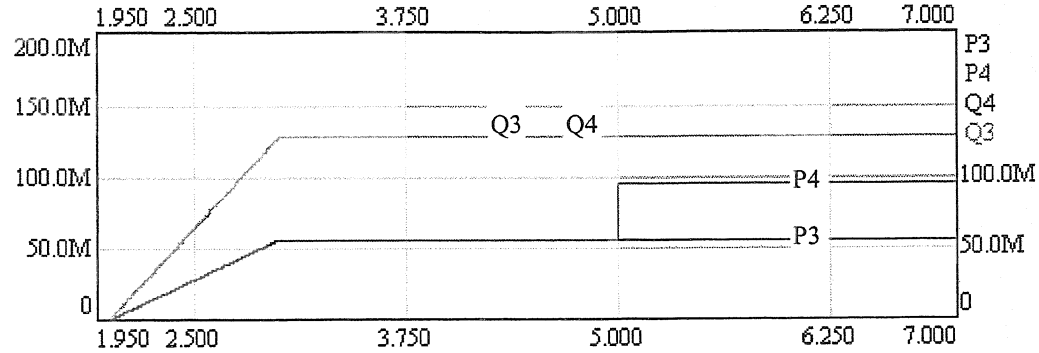


Rotor angle

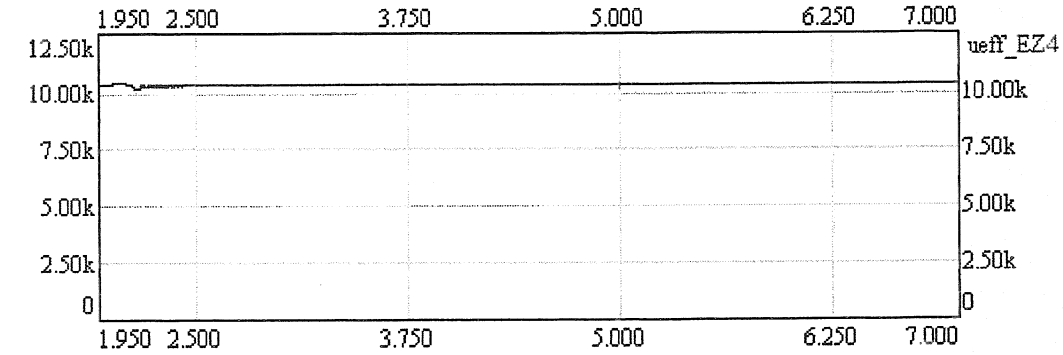


(d9) S=280MVA, cosq=0.4 (worse parameter of generator)

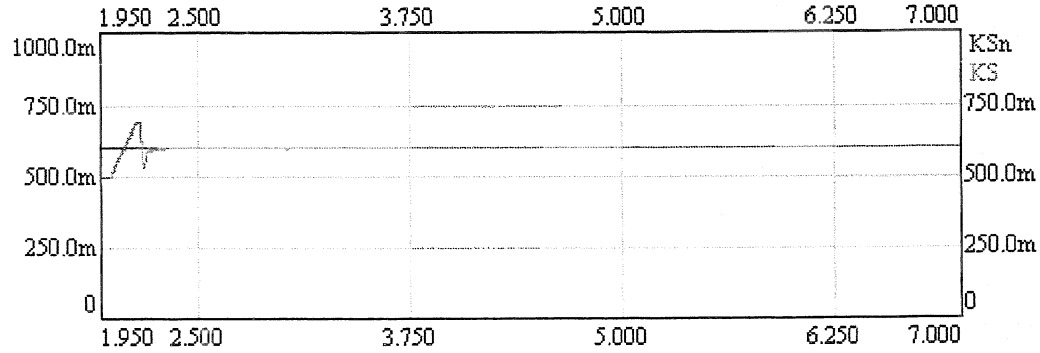
Power



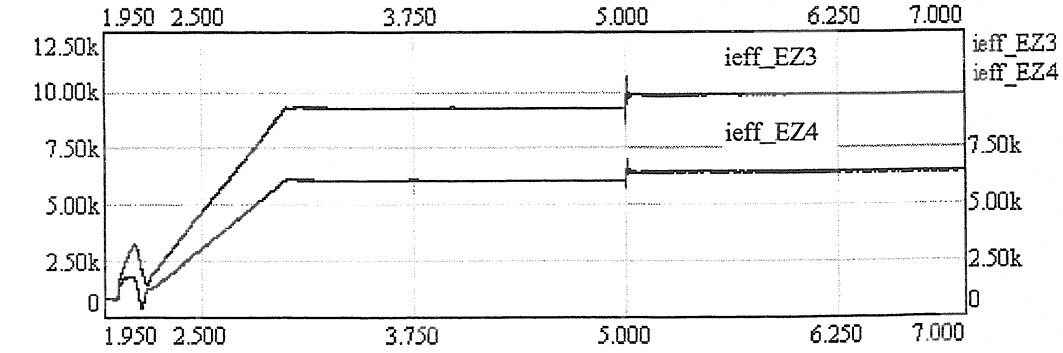
Bus voltage



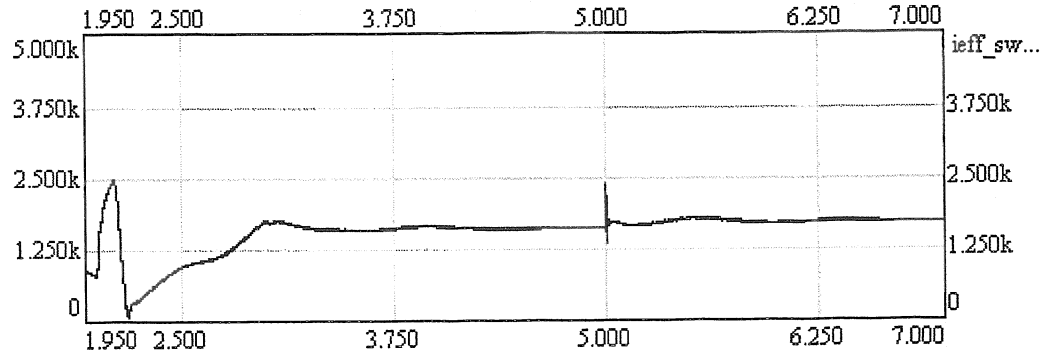
Power distribuation



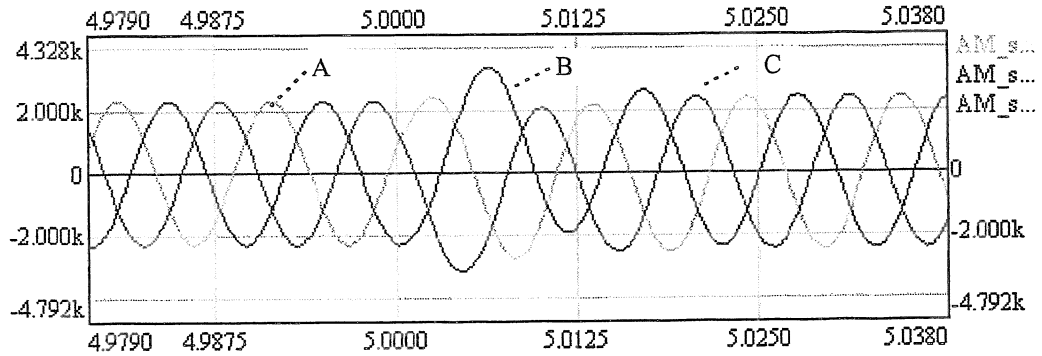
Generator current



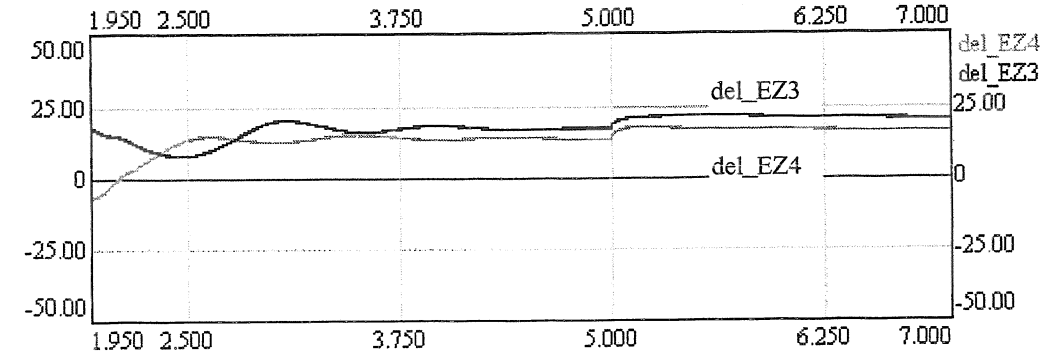
Switch current



Three phase current of switch

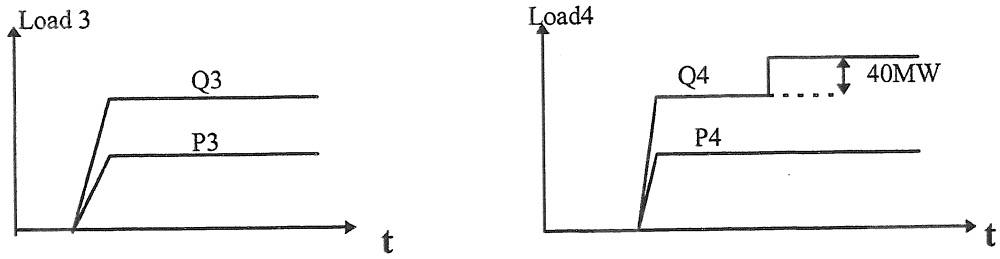


Rotor angle

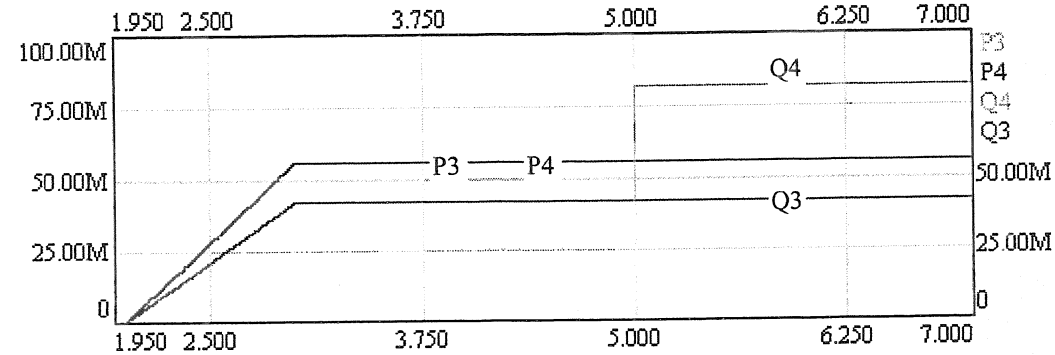


(e) Behaviour in step function and changing power factor load

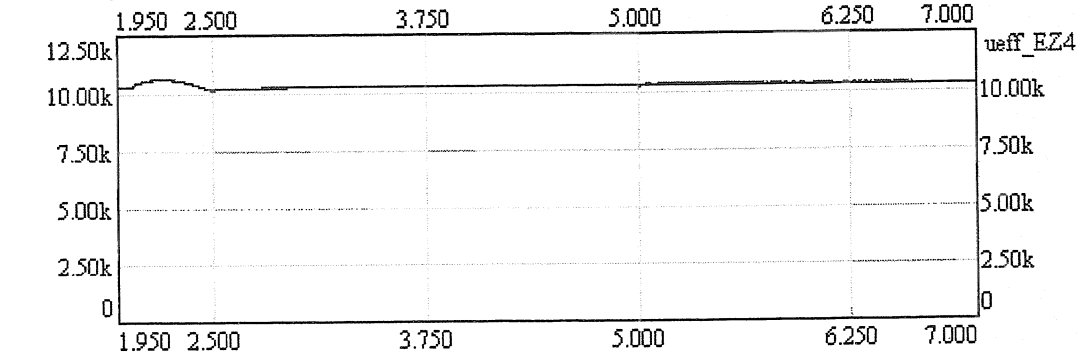
(e1) Step power near EZ4(p3=P4, Q3=Q4, S=140MVA, cosq=0.8)



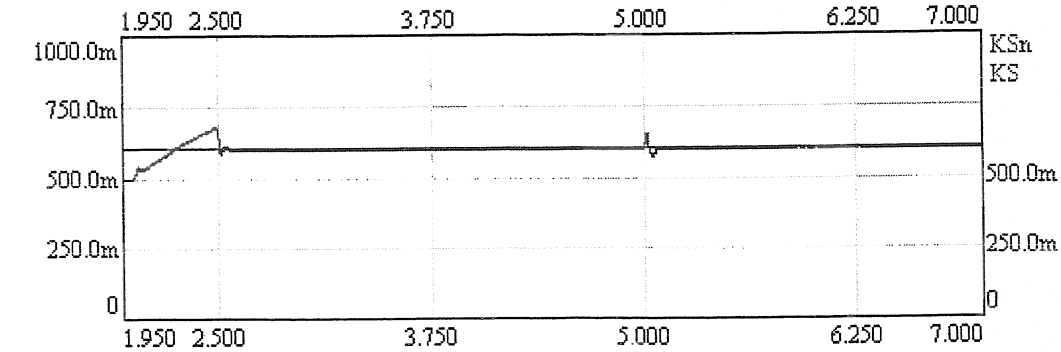
Power



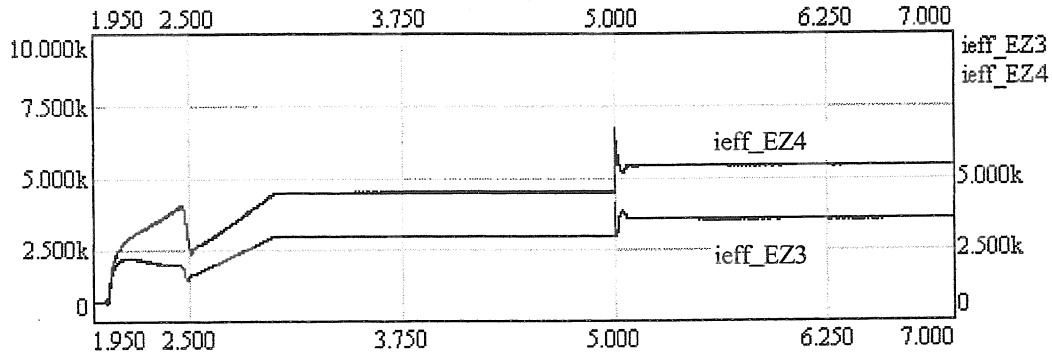
Bus voltage



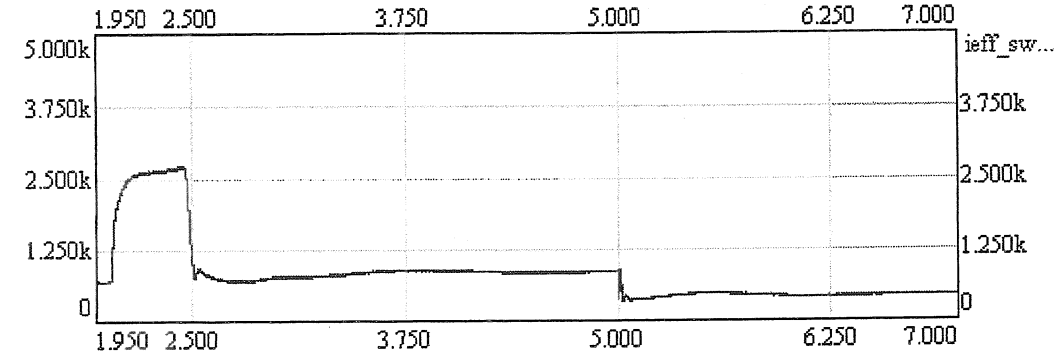
Power distribution



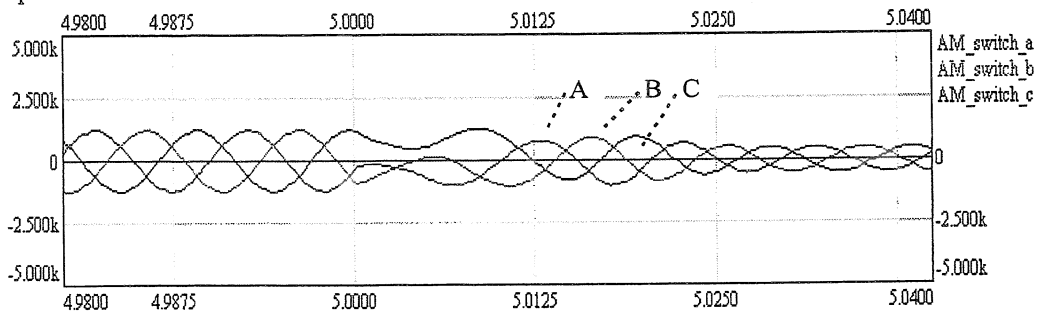
Current of generators



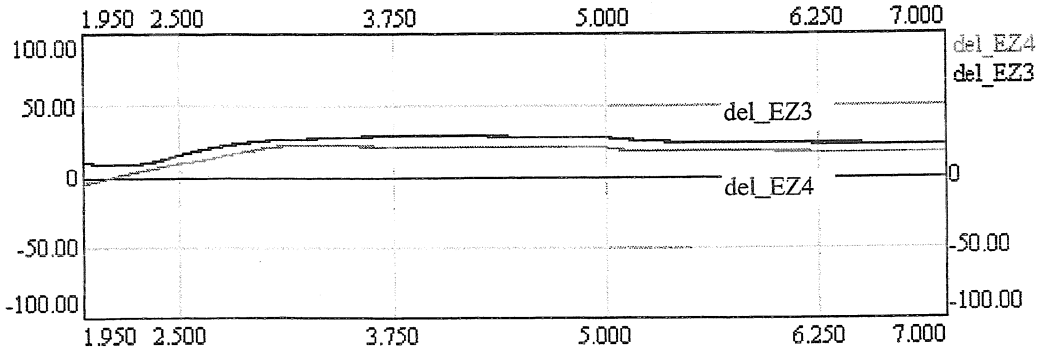
Switch current



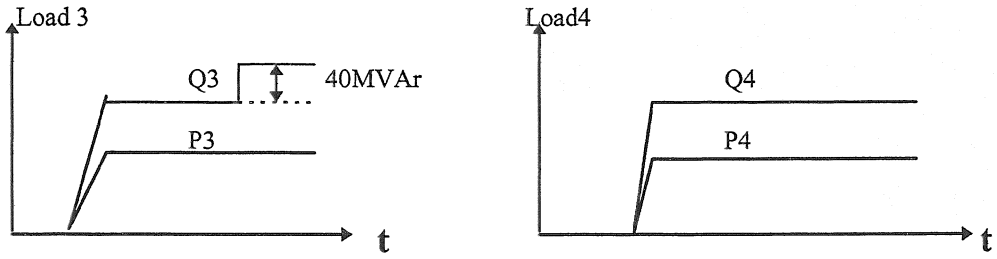
Three phase switch current



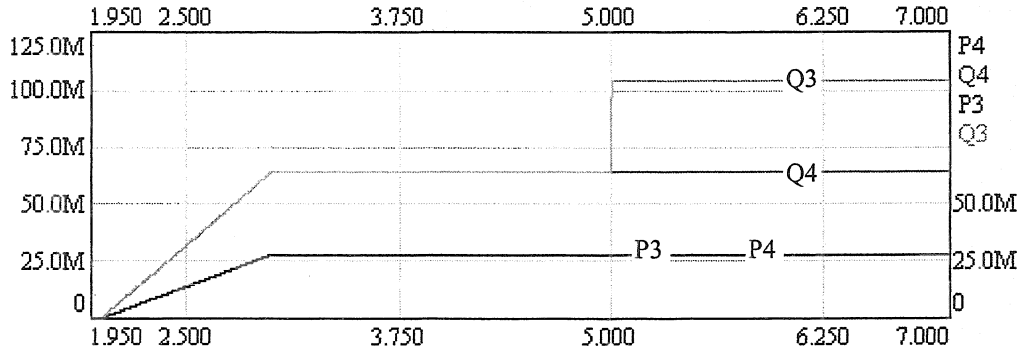
Rotor angle



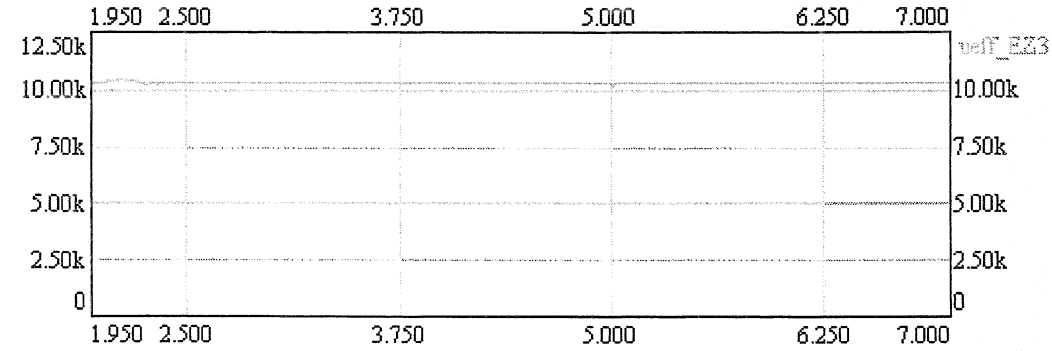
(e2) Step power near EZ3 side (S=140MVA, cosφ=0.4 , P3=P4, Q3=Q4)



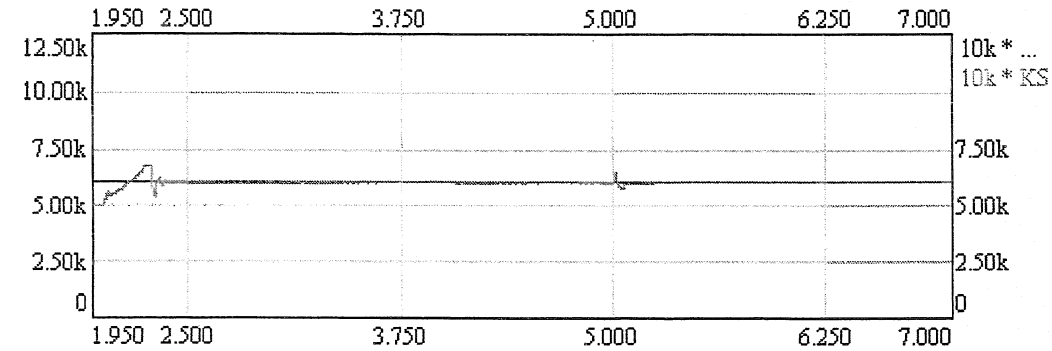
Power



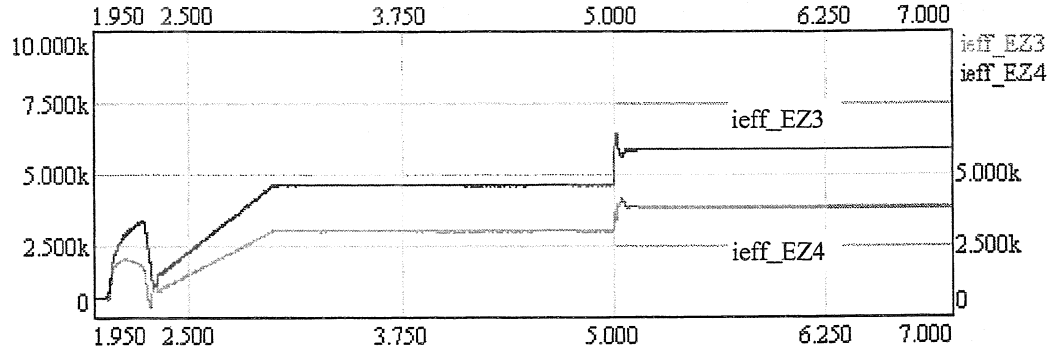
Voltage



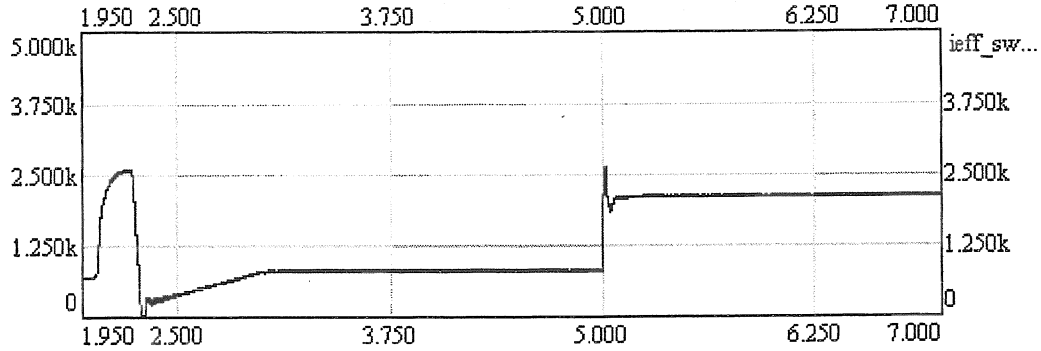
Power distribuation



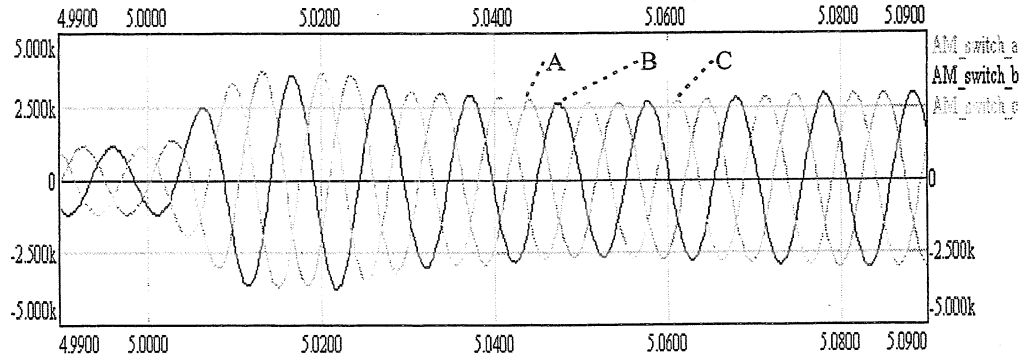
Generator current



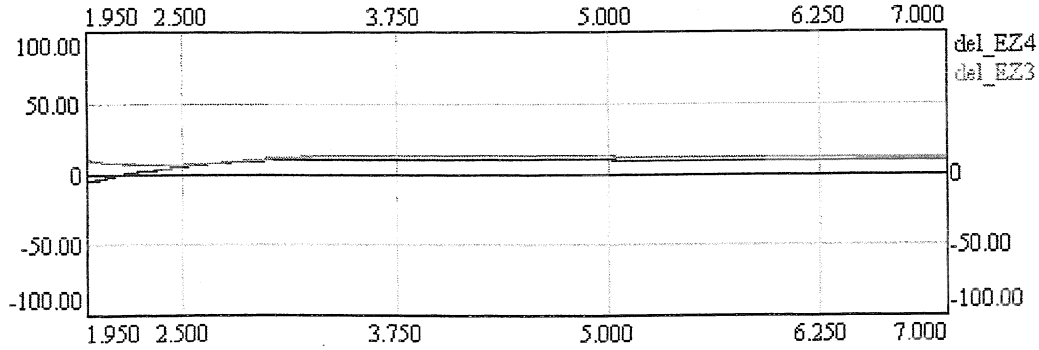
Switch current



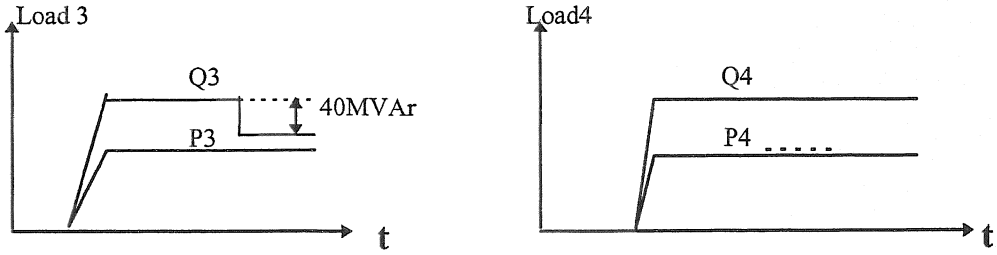
Switch current of three phase



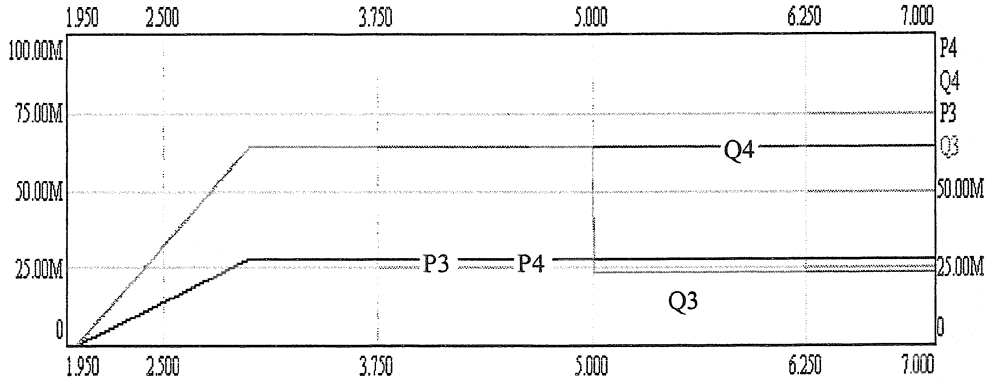
Rortor angle



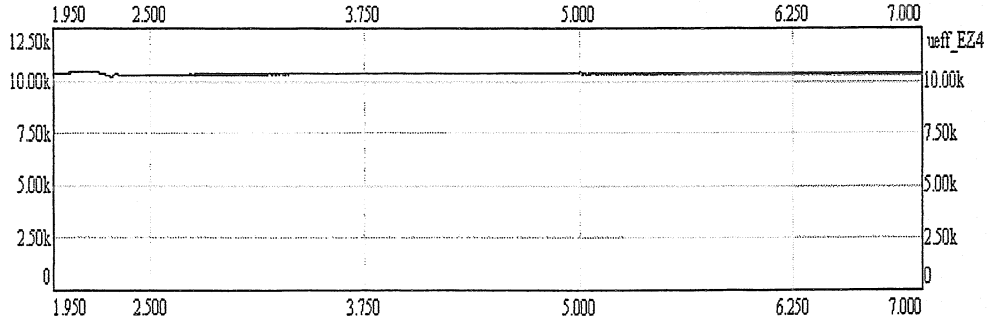
(e3) Negative step power near EZ3 side (S=140MVA, cosφ=0.4, P3=P4, Q3=Q4)



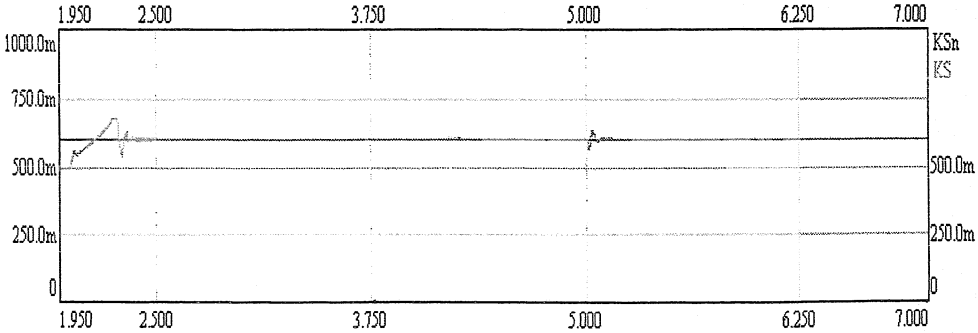
Power



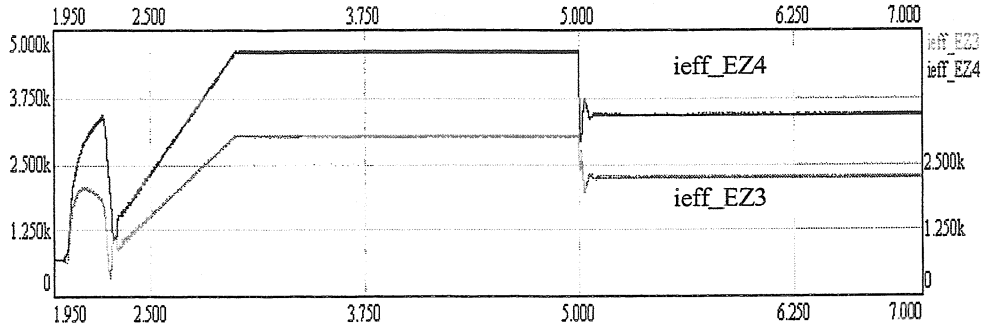
Voltage



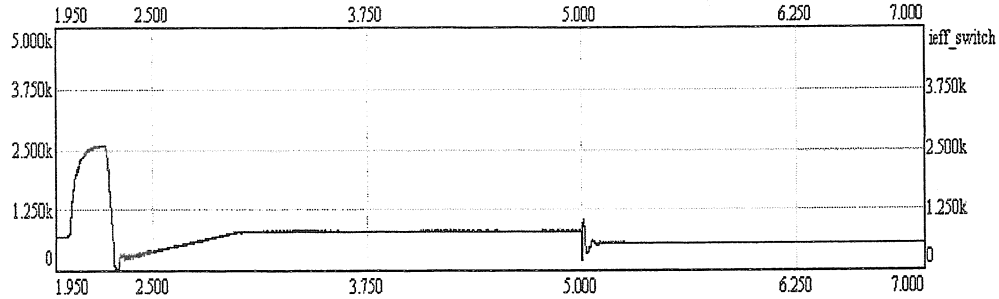
Power distribuation



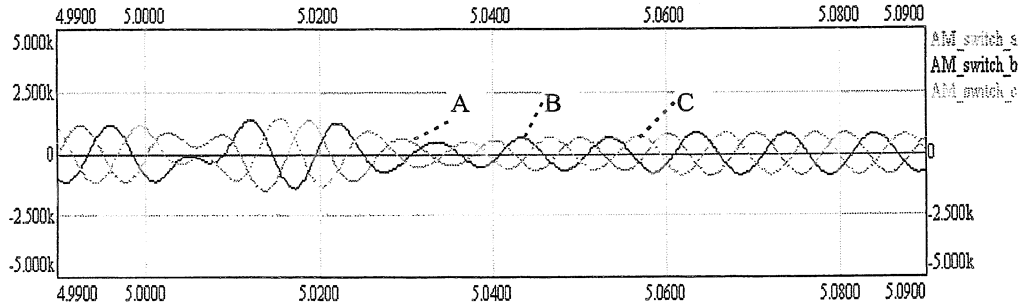
Generator current



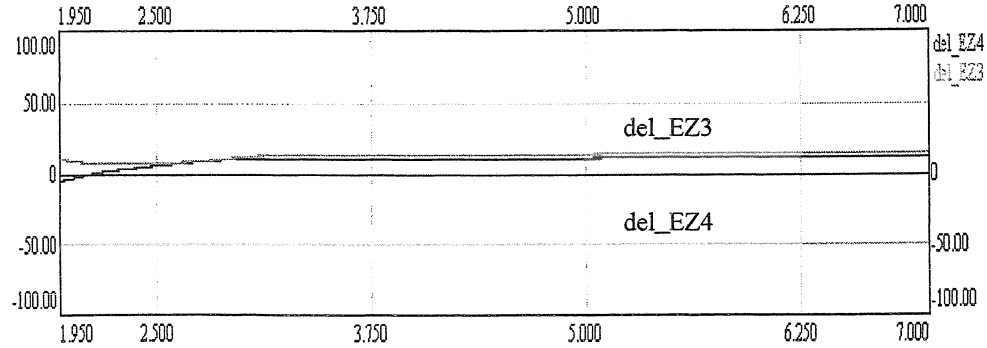
Switch current



Switch current of three phase



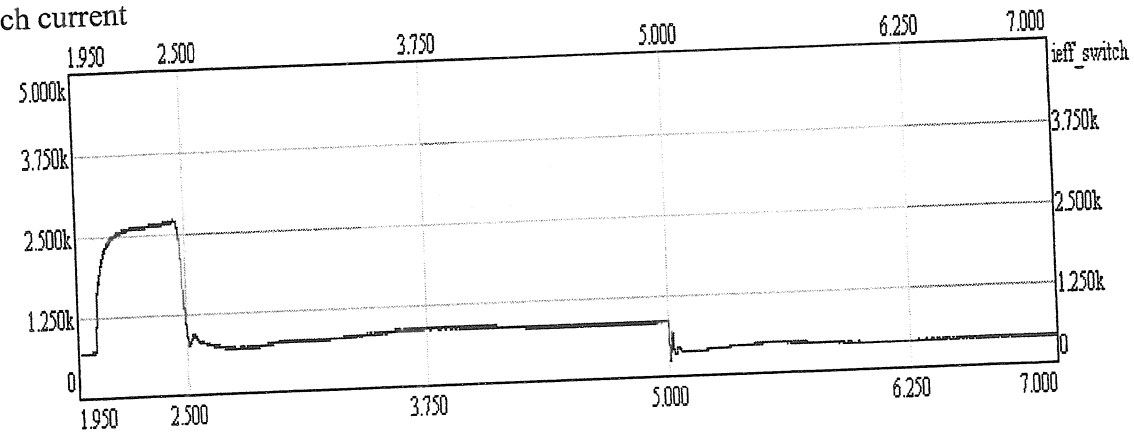
Rotor Angle



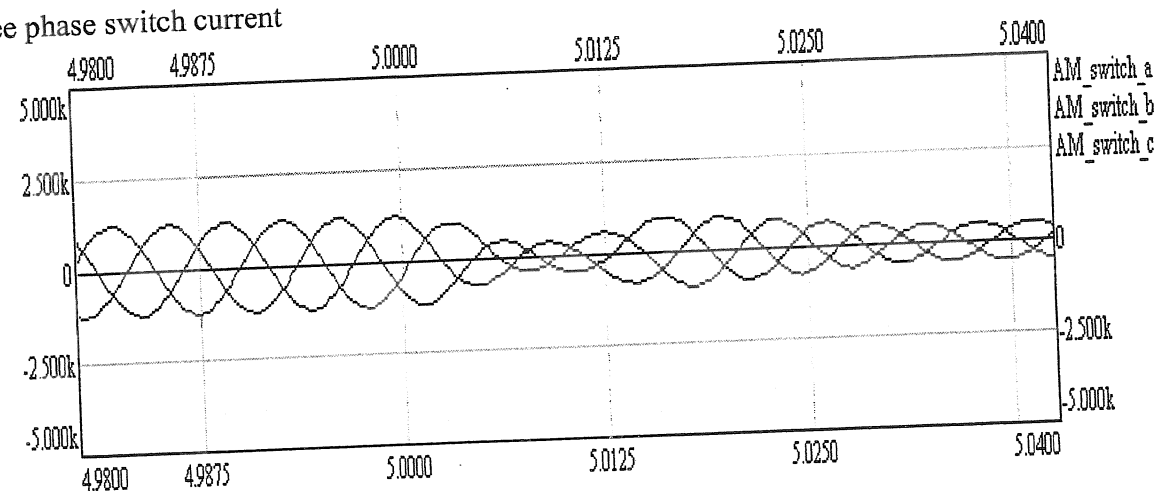
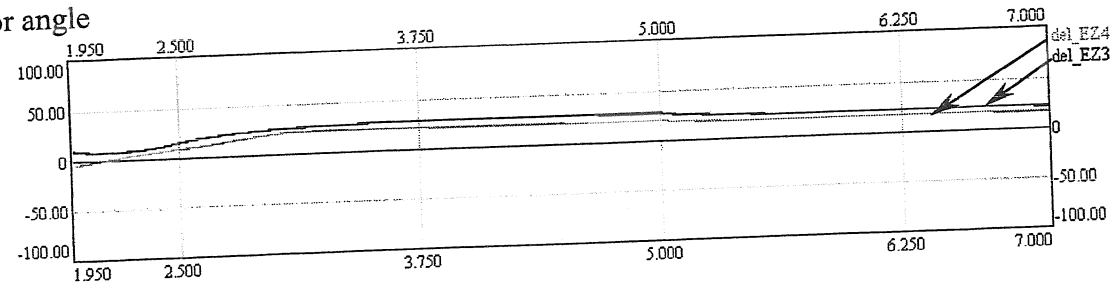
Supplement to the simulation results shown on pages 121 and 125

The results shown on pages 121 and 125 can only be interpreted as approximate results. The transient behaviour is not shown correctly because problems with the automatic time incrementation scheme occured. A new simulation with more realistic input data (rise time of power 10 ms instead of 1 μs) leads to the following results (case (e1), see page 120-121) :

Switch current



Three phase switch current



Rotor angle