Plant Identification and Tuning Controls An EMTP case

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This paper proposes a technique to tune and optimize controls in a power system useable in an EMTP network like a stability program. The controls concerned by theses objectives are PSS and other power modulation functions. The method consists of three steps: first, identify the system with PSS in open loop condition with a white noise source and validate the {a,b,c,d} plant's matrices, second validate the "plant's matrices & controls" in closed loop with EMTP time domain, and third, optimize the control parameters to minimize the modal energy, a scalar derived from the system's matrices. This method was developed early and used at Hydro-Quebec with its stability program. The challenge here is to apply this method working in a no noise environment, to work too in EMTP with non linear equipments. All the Id&Optimization routines are computed in MATLAB.

***Keywords*: plant's identification, tuning control, PSS.**

I. Introduction

THe Hydro-Québec generating equipment connected to the transmission network is made up of 95 power plants whose ratings vary from few megawatts to 5300 MW, for a total of 40 000 MW of installed capacity. 30 of these 95 have static excitation systems equipped with power system stabilizers (PSS), and represent 80% of the total capacity installed. Hydro-Quebec has been using for over a decade, a modal analysis technique [2,3,4], based on a state-space matrix {A,B,C,D} of the network - power station system dynamics, used to tune PSS's parameters. This representation is computed in MATLAB™ from time domain results calculated by classical stability software. The method's step-by-step full description was documented in a panel session [1] and is resumed in this paper for the benefit of the community. On the other hand, more than 2000MW of new power plants using non-linear switching technology such as wind farms will be in service in the next few years. For this type of equipment, an EMTP model has a full representation in the 0-kHz range with its power electronic devices, controllers and PSS, without any simplification.

This paper presents how the state-space approach could be used in a noisy environment like the EMTP program with a few minimal precautions. Henceforth, EMTP may reproduce dynamics oscillations with automatic voltage regulator (AVR) and PSS models as for any stability program.

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Harmonics and power oscillation phenomena are independents; this method successful grab the liner matrices related to power oscillations from an environment include 0-kHz harmonics.

II. Methodology

This method is based on a power plant's linear state-space identification approach, working like a spectrum analyzer. The methodology consists of importing time domain results from EMTP in MATLAB to compute linear analysis:

- split the power plant into two groups, one machine and N-1 machines group,
- use random signals in addition to the power modulation functions output. For a synchronous machine, that corresponds to Vaux exciter's input,
- trigger signals are the inputs to the power modulation functions, plus one or two PSS inputs from other power plants remotely located in another place in the network,
- repeat this sequence twice, without (open loop) and with (close loop) your power modulation functions,
- import the open loop time domain results into MATLAB, use N4SID algorithm and synthesize F(s). Validate F(s) with EMTP's time domain,
- import the close loop time domain results, compare and validate H(s), the close-loop system define by F(s) and G(s),
- use minimal search functions with controller constraints corresponding to the physical limits of the parameters and performance limitations. The objective, the modal energy of H(s), is a well adapted scalar for a power system.
- test the new parameters performance with major events in time domain.

The identification techniques described in [3,4] are upgraded recently to achieve accurate modal analysis of all modes of interest by using, first, a new pseudo-random control source with sufficient spectral energy in the 0-10Hz range and second, more than one random source could be used in the same simulation, for multiple-inputs matrices. These sources and the Numeric For Systems Identification routines (N4SID) are used successfully [6] for 0-3kHz range and reused for the 0-10Hz stability transient range examined in this paper.

III. Governability and Observability Notes

A Multiple Input Multiple Output (MIMO) identified system has the following features: two inputs, three or four outputs as show in Fig.1. Two inputs are required to govern and observe the two local modes: the plant's inter-group and the plant's all-group modes. The inter-group mode is the oscillation between one group against others and never goes out of the power plant. The second mode is the interaction between the power plant and the network, all groups in phase. Our experience shows the inter-group mode is less dampened than the all-group mode [1]. A single input, single output (SISO) or SIMO system is easier to manipulate but only the "plant all-group" mode will be represented in this case, in the matrix A.

The study of the power plant is achieved as follows: the N groups are split into two generators: one representing a single machine and the second N-1 groups. Thus, two outputs representing the PSS input are triggered as indicated in Fig.1.

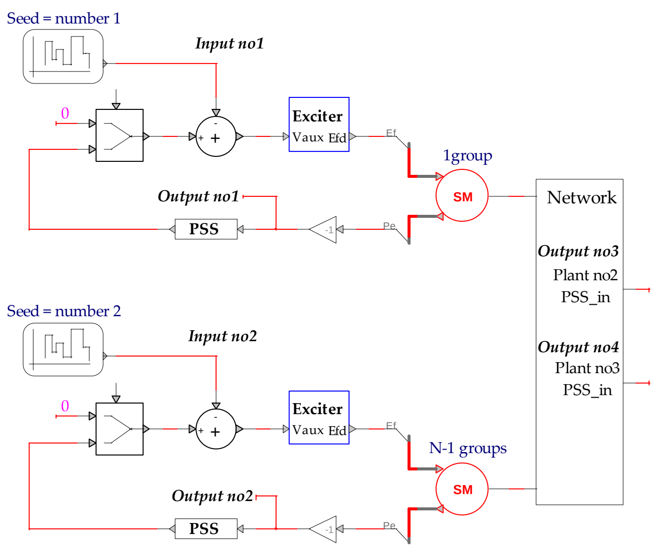


Fig.1. EMTPWorks. State-space set-up for open and closed linear analysis.

The inter-area oscillations may limit transit on lines. To synthesize adequately the behavior of this mode, it is required to observe a third and/or a fourth output, usually the electrical power of a second and third power station remotely located in another place elsewhere in the network indicated in Fig. 1. That will be useful to tune the controls in accordance with two objectives: damp the local and inter-area modes. Depending on the network and the controls, it could be impossible to damp both correctly, but we are seeking the best compromise. It is another discussion but the PSS2A (1992) and the PSS4B (2005) were designed on purpose to avoid this compromise.

According to the F(s) structure, G(s) must have four inputs - two outputs structure as show in Fig. 2a, based on the IEEE PSS1A model which is installed in the power plant under study.

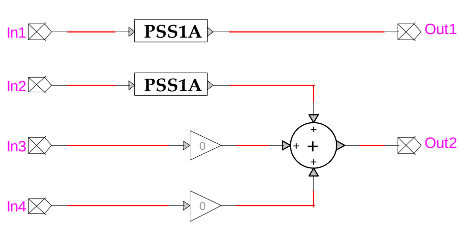


Fig.2a. Structure of G(s) 4in-2out, connected with F(s) 2in-4out.

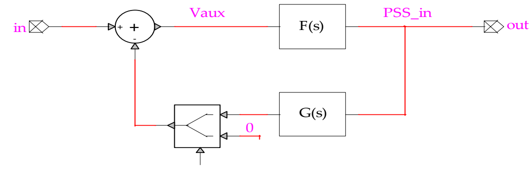


Fig.2b. Schematic. State-space set-up for open and closed linear analysis.

IV. F(S) AND H(S) VALIDATION NOTES

Two important tests are required to validate F(s). First, superimpose the outputs from EMTP and F(s) which have the same entries: the two independent pseudo-random sources. In this case, the PSS gain is set to 0 in the EMTP file. Secondly, the *most important test*, superimpose a second set of time-domain curves from EMTP and H(s), where H(s) is derived following this basic equation (1) and show in Fig. 2b. G(s) is defined according with the initials PSS parameters set-up simulates in this second EMTP file.

$$H(s) = \frac{F(s)}{1 + F(s).G(s)} \qquad (1)$$

When the frequency and the damping from H(s) are close enough to time domain results, *it means the G(s) impact on H(s) is predictable*. Consequently, the optimization routine results will be reliable for our objective, tuning PSS.

Fig. 3 shows for both 1 group and N-1 groups, the white noise source (Baseline Wander), two types of inputs for plant identification, Pe and PeFiltering, and Edf, the field machine. Basically, the white noises must have these two characteristics:

- sufficient spectral energy between 0-5Hz, the bandwidth of electrical oscillations in a network; a sample rate of 0.5s gives energy up to 10Hz,
- but these outputs should be limited in gain to avoid signals touching any limits, for example exciter machine limits set at ±6pu. If not, the responses are not linear and the ID doesn't work adequately.

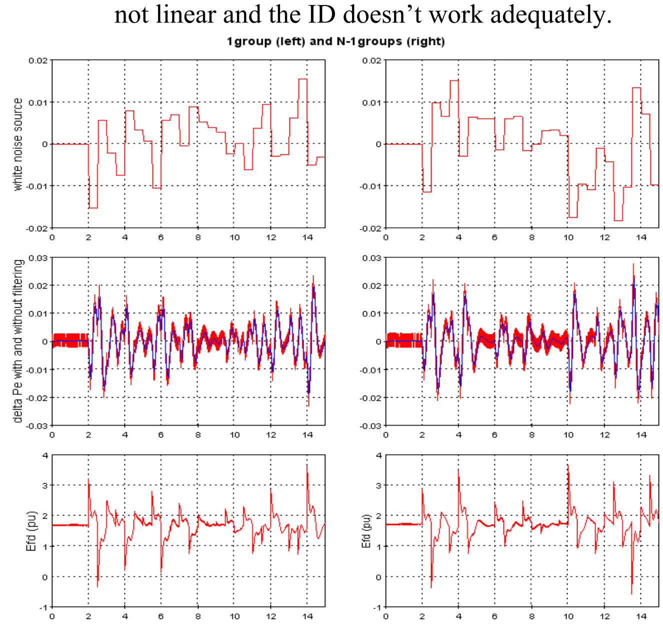


Fig.3. Results from EMTP time domain in open loop.

The electrical power Pe is the common input into the stabilizer. The PSS always have filtering functions, Fig. 4 shows the stabilizer's transfer function; the wattmeter time constant is represented by $T_{6,}$ set at 0,035s. In Fig. 3 and 5, the red and blue curves are the signals before and after filtering. They demonstrate how the Pe/Filter, is effective and gives clean signals for observation; otherwise, using Pe as an input, the N4SID routines cannot work correctly if too much harmonics are present in the network and reflected in Pe, such as the case in Fig. 8.

The wattmeter acquisition filter is an invariant parameter. The selection of this output means the filter transfer function was removed from G(s) and goes to F(s).

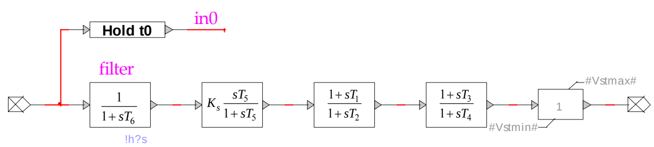


Fig.4. IEEE PSS1A transfer function. Pe is filtered by the parameter T_6

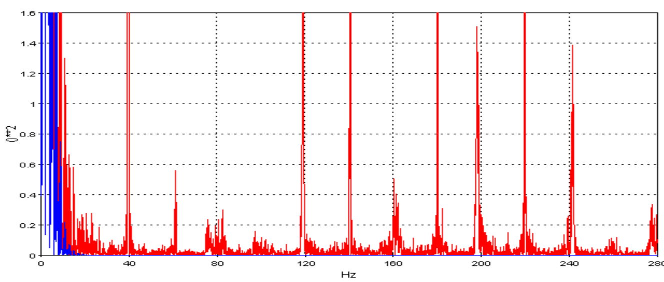


Fig.5. Electrical power signals spectral energies: before (red) and after (blue) filtering.

V. F(S) AND H(S) VALIDATION RESULTS

The time domain results were interpolated with Δt=0,050s before being imported into the N4SID routines and the time frame used is T_{start}=1 or 2s, T_{stop}=10 or 15s. Even the machine devices were quasi-perfectly initialized in EMTP-RV, in Fig. 3 look at Pe and Efd between 0-2s, it is preferable to wait one or two seconds before starting this type of linear analysis.

The system order of F(s) is an estimated value given by the user at the beginning of the routine. For an electrical power system, only *one or two pairs of modes are generally required for each triggered output*. The four outputs are defined in Fig. 1, nos. 1-2 locals and nos. 3-4 elsewhere, theses output levels are present at 1/20 of local measurements as show in Fig. 6.

As indicated before, the same white noise sources in EMTP were used as F(s)'s inputs. The Total Harmonic Distortion (THD), the distortion between the red and the blue curves in Fig.6 was used as criteria. Less than 15%, it is generally acceptable. Also, with visual inspection i.e. engineering appreciation, we may decide if this ID was good or not: little acceptable shift in frequency, damping, amplitude or phase errors may introduce THD. In this example, this ID is definitely good, the minimum THD was obtain with a system order set to 16.

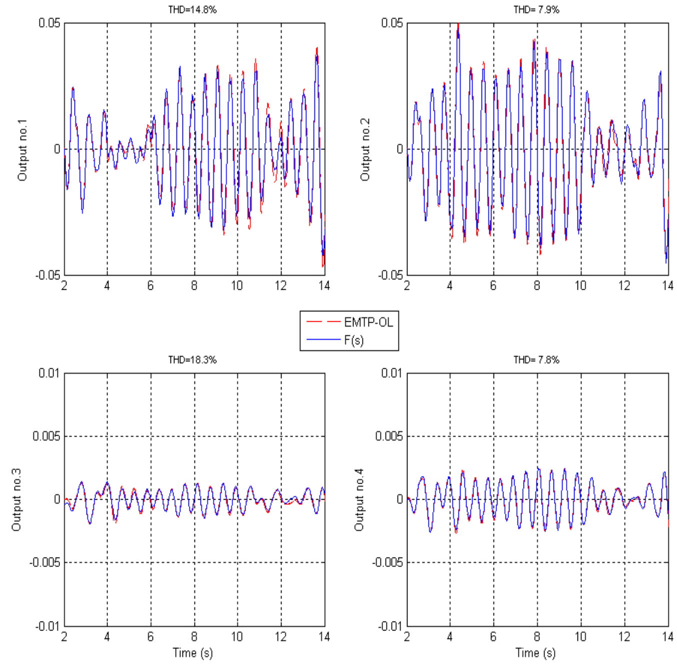


Fig.6. Four outputs - Validation of F(s) with EMTP, PSS in open loop.

Fig. 7 illustrates the *validation between H(s) and time domain results*. This is an important statement: when H(s) is also comparable with time domain, *F(s) can be considered as perfect for tuning controls* and the effect of the PSS is definitely predictable and for all modes: the inter-group mode, the plant-allgroups mode, and inter-area modes.

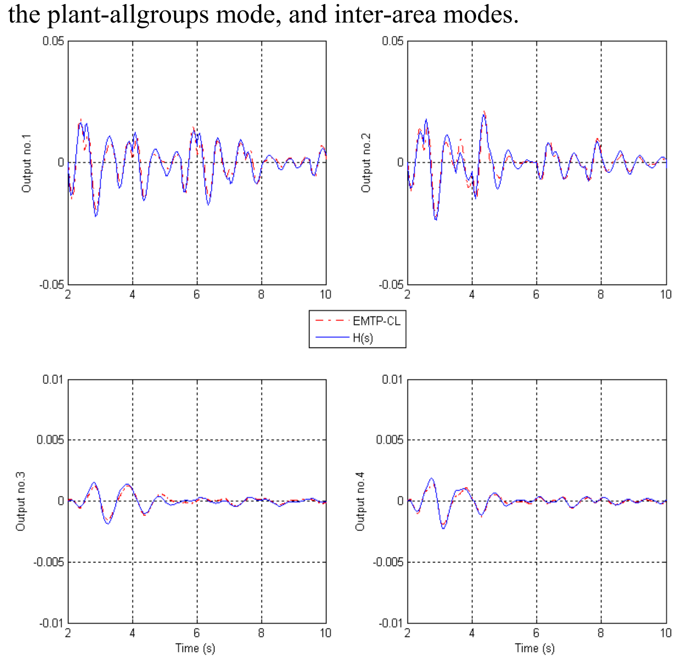


Fig.7. Validation of H(s) with EMTP, PSS in close loop.

All these two precedent EMTP simulations do not yet have harmonics. Examine and repeat this previous ID when harmonic current sources are close the power plant. To prove immunity of N4SID routines, the harmonics current level was set to be significant; Fig. 8 shows the harmonics on the high voltage power plant side.

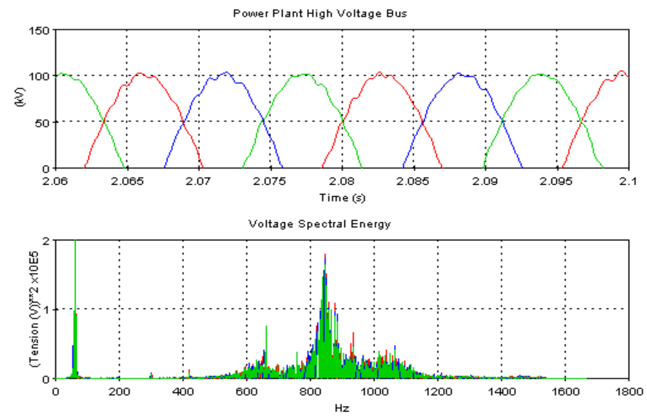


Fig.8. Power plant high voltage affected by harmonic sources.

With this new harmonic time domain case, we obtain a second F(s) and derive also a second H(s). This second H(s) is validated in Fig. 9: the frequencies and their damping are nicely equal with EMTP.

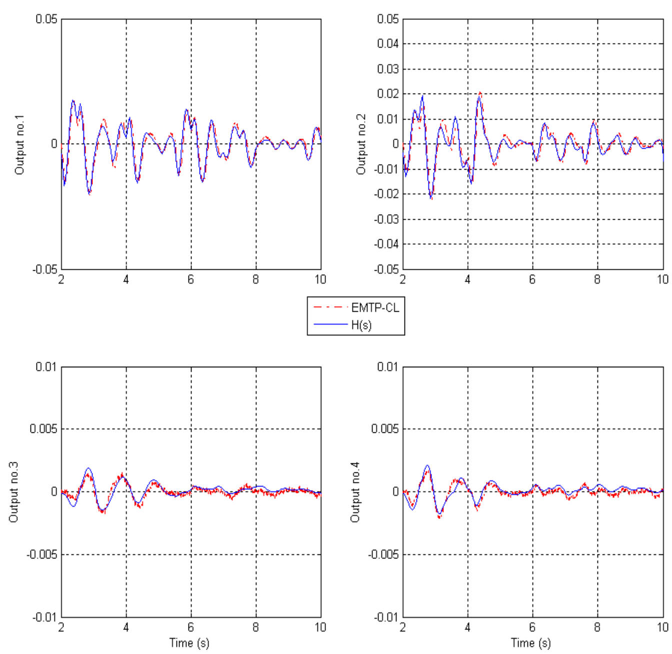


Fig.9 Harmonics included - Validation of H(s) with EMTP.

VI. Tuning PSS with Constraints

M. Kamwa [5] has developed a scalar f(x) derived from H(s) that requires only a single user-defined parameter `t_optim` (sec), which represents the modal system energy estimated during this time window (typically 5s): the lower the f(x), better is the stability system. In control jargon, f(x) is called the cost function. With this approach, H(s) is study as a minimal function problem with G(s) having four or six degrees of liberty according to the number of parameter set in your PSS. In other word, find the best transfer function for the stabilizer installed in this particular power plant. F(x) is defining in `H_ModalEnergy` in (4).

The robust and optimal control design [1,5] depends here on a proper definition of all constraints underlying the good operation of a power system stabilizer in time domain:

- Lower and upper physical limits of time constants and gains that can be implemented in practice on the existing power based stabilizers. Define with vlb and vub in (4).
- Constrain the stabilizer gain $|G(j2\Pi f_1)|$, with $f_1 \approx 1$ or 2Hz frequency according to the principal mode existing at the power plant. High gain of G(s) may be good to control F(s) in small-signal domain but could be unusable in time domain because the output will reach the limits (±0,10 or 0,15pu) too often, more than three times when solicited during a severe event. Define in `pss1aConstraint` in (2).
- Constrain the stabilizer phase of $G(j2\Pi f_2)$ $f_2 \approx 0{,}5$Hz, i.e. your inter-area mode, to a value and between ± 5°. This constraint holds the required phase of G(s) at this frequency. It is optional and not particularly required if you trigger a third or fourth output properly chosen. Also define in (2).

Here fellows a summary of the syntax of optimization functions used by the author:

```
constraint=@(pss_x)pss1aConstraint(pss_x,...                (2)
    'pss1a_T6na_4x2',[Fref Fref_magMax]);

objectif=@(pss_x)H_ModalEnergy(pss_x, ...                   (3)
    'pss1a_T6na_4x2',Fsys,t_optim);

[pss_x_af,f_ap]=fmincon(objectif, ...                       (4)
     pss_x_in,[],[],[],[],vlb,vub,...
     constraint,options);
```

Where
- `pss1aConstraint`, the constraint function derived from G(s), Fref and the maximum gain at this frequency,
- `H_ModalEnergy`, the cost function of H(s), working with structure of F, G(s) `pss1a_T6na_4x2.mdl` and `t_optim`.
- `pss_x` is the parameter's vector to be optimized, `pss_x_in` initial values, `pss_x_af` after optimization,

VII. A Tuning Case Including Harmonic Sources

The case with harmonics shown in Fig. 8 and F(s) previously validated in Fig. 9, were used for this case. The constraint we use is gain at f_1=2Hz, the initial $G(j2\Pi f_1)$ gain is 0,20. The tuning case presented here will be done with a gain set at 0,40, an engineer's choice, and consequently the constraint margin is -0,2.

Table I presents the echo of the `fmincon`'s used. The new setting of G(s) was found after 300 iterations and 4-5s of CPU time. Sometimes the `fmincon` needs 75-200F-count, according to the network represented by F(s), the degree of liberty and your first choice of G(s).

According to the transfer function in Fig. 4, the initial and final parameters are:

- Initial parameters:

  T1=0,03s; T2=1,04s; T3=0,026s; T4=0,0s; T5=0,102s; Ks=2,9; (5)

- Final parameters:

T1=0,115s; T2=0,360s; T3=0,00s; T4=0,00s; T5=0,36s; Ks=1.08; (6)

TABLE I - OPTIMIZATION ROUTINE ECHOS.

Iter	F-count	f(x)	Max constraint	Directional derivative
0	8	15.5707	0	
1	20	14.7441	0	-16.7
2	29	11.2	2.18E-17	-5.49
3	37	16.5849	2.17E-19	-14.5
4	46	16.2337	3.69E-18	-1.8
5	55	16.0141	1.74E-18	-1.49
6	67	14.1509	6.07E-18	-1.82
7	77	10.4529	0.03053	-7.32
8	85	10.8728	2.16E-32	-1.27
…				
32	289	10.3787	1.60E-19	-0.00204
33	297	10.3787	1.15E-18	-0.00413
34	305	10.3787	6.51E-19	-0.0063

Figures 10 and 12 summarize in phase and time domains, the performance of the final parameters. The G(s) Bode diagram of Fig. 10 shows the final gain within the constraint 0,4@2Hz. The phase response has changed also except at 2Hz, -10° is conserved by `fmincon`.

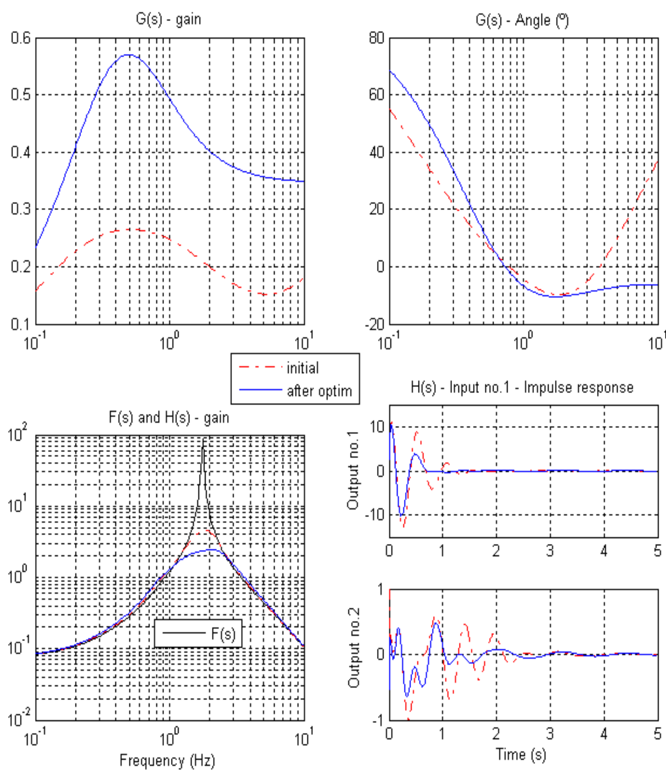


Fig.10. Bode diagram of F(s) and H(s). Time domain of H(s).

In a two by four MIMO system, eight transfer functions were included. The time domain curves of H(s) where the impulse response between input no.1 and output no.1 and no.2.

The controller performance is quantified with a few indicators such as gain and phase margins, damping of principal modes. At the power station, Table II shows the gain margin decreases from 33 to 25 dB, this is not critical since it is well established from control system practices that appropriate robustness is still achieved with a minimum of 6dB gain margin.

TABLE II
H(S) - NATURAL FREQUENCY AND DAMPING

	Natural frequency (Hz)		**Damping**		**Gain and phase margin**	
	Initial	After	Initial	After	Initial	After
Inter-groups mode	1.8	2.4	0,23	0,47	33 dB	25 dB
All-groups mode	1.6	1.5	0,18	0,28	-----	-----
Regional mode	1.6	1.2	0,68	0,55	80°	64 °

Other indicators are root-locus plots. They illustrate improvements of the system dynamics using the new settings and indirectly the good result achieved by the optimization functions as well. But the `rlocus` function works only with a SISO function. When G(s) had two inputs, the root-locus have to be calculated twice as documented in Fig. 11 and superimposed on the same plot, see Fig.12. This will be done for initial and final parameters. This is the best way to observe the inter-group and the all-group mode trajectories: the reader may note theses modes are instable in open loop at eleven radians, notice red **X** markers that go to green **X** markers in nominal close loop gain.

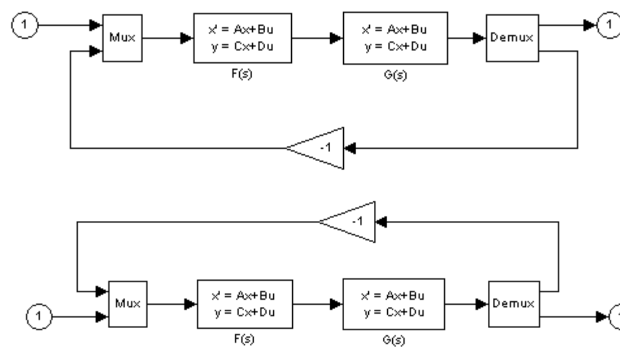
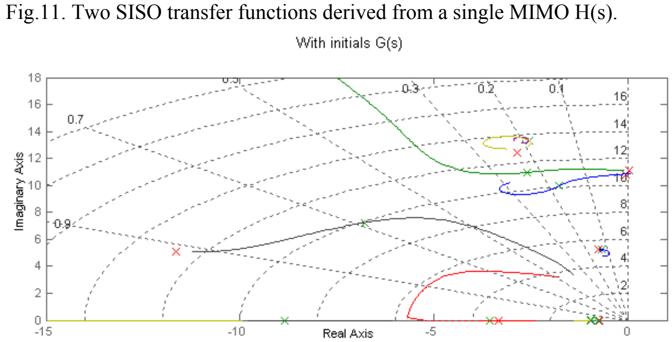


Fig.11. Two SISO transfer functions derived from a single MIMO H(s).



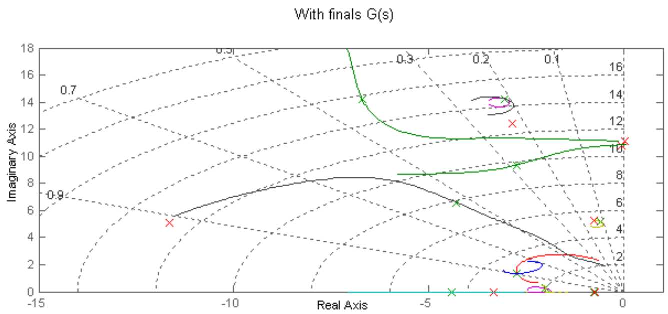


Fig.12 Root locus trajectories with G(s) gain varying 0 to 10. Gain=0 "red x"; gain=nominal "green x". Top, initial parameters - bottom, final tuning.

All these results demonstrate the relevance of the proposed modal energy index as the cost function to be minimized. Overall, constrained nonlinear optimization allows attaining the maximum damping available within the physical limits `vlb` and `vub` used in Equ. 4.

VIII. Stability Improvement

The proof of this approach is incomplete without time domain stability in case of a major perturbation. These tests included loss of lines, single and three phase faults and other events according to the conception criteria used by the utility. For the present paper, a three phase fault followed by a loss of line is simulated. This event is done with the two sets of PSS parameters in Equ. 5 and 6. Fig. 13 shows the power output of the machine (left) and its PSS output (right). The new accepted damping on Pe can be observed and the PSS output, is higher as provided, because the final gain is set at 0,4 compared to 0,2.

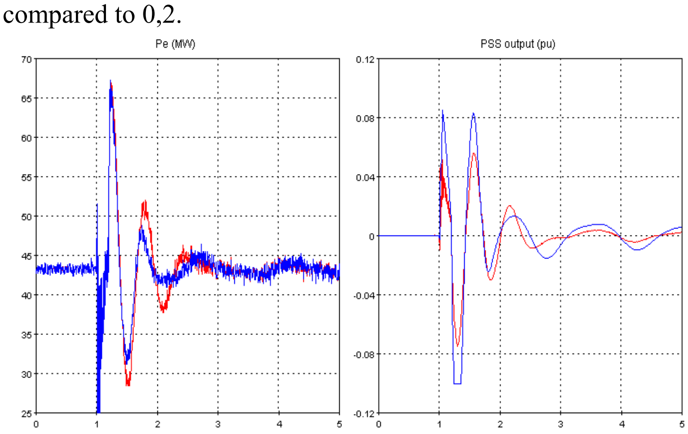


Fig. 13 Loss of line in EMTP. Initial (red) and after Optimization (blue).

IX. Conclusions

This work presents a step-by-step method to tuning controls such as PSS in a noisy (or not) harmonics environment, when non-linear technology exists in your time domain simulation. This method is based on a power plant's linear state-space identification approach, working like a spectrum analyzer. The methodology consists of:

- split the power plant into two groups, one machine and N-1 machines group,
- use random signals in addition to the power modulation functions output. For a synchronous machine, that corresponds to Vaux exciter's input,
- trigger signals are the inputs to the power modulation functions, plus one or two PSS inputs from other power plants remotely located in another place in the network,
- repeat this sequence twice, without (open loop) and with (close loop) your power modulation functions,
- import the open loop time domain results into MATLAB, use N4SID algorithm and synthesize F(s). Validate F(s) with EMTP's time domain,
- import the close loop time domain results, compare and validate H(s), the close-loop system define by F(s) and G(s),
- use minimal search functions with controller constraints corresponding to the physical limits of the parameters and performance limitations. The objective, the modal energy of H(s), is a well adapted scalar for a power system.
- test the new parameters performance with major events in time domain.

X. Acknowledgment

The author gratefully acknowledges the contribution of I. Kamwa whose contribution made this work possible.

XI. References

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