DESIGNING CONTROLS FOR NON–LINEAR SYSTEMS WITH ELECTROMAGNETIC TRANSIENT PROGRAMS

by

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1. INTRODUCTION

Power electronic controllers in power systems are non–linear by nature and are required to operate satisfactorily over a wide range of system conditions. Dc links and static var compensators (SVC's) are the the traditional power electronic controllers widely used at the transmission level. At the industrial level, variable speed drives, cycloconverters, dc rectifiers and power supplies are applied. Non–linearities in their performance are due to signal transmission delays, limits and non–linear gains in their controls, discrete firing intervals of diode, thyristor and GTO valves as well as the effects of transformer saturation.

The general way of dealing with non–linearities in controller design is to linearize their performance around an operating point and designing controls by usual linear methods. Although a perfectly rational approach, the resulting design must be rigorously tested to ensure satisfactory operation under extreme conditions and large signal disturbances. Electromagnetic transient programs generically designated herein as "emtp" are most suitable for such tests because of the ease and ability to represent large systems with all non–linear functions and features. In fact, emtp can be used as a controller design tool. Use of PSCAD™/EMTDC™ [1] as the example emtp is applied herein to outline power system non–linear controller design.

KEYWORDS

Emtp – electromagnetic transients program – non–linear controls – power electronic controllers – control design.

2. MODELLING THE NETWORK

Electric power systems with fast acting power electronic controllers are not the easiest systems to model. The commonly applied state variable approach is usually a challenging exercise if the controls, discrete valve firing process and the power system network are to be incorporated in the design model.

O.B. Nayak et al. [2] have introduced the concept of "Control Sensitivity Index" or CSI which is a constant based on the quasi steady state network equations, assuming fundamental frequency ac voltages. CSI considers only the steady state instability associated with a control mode. CSI is defined as the transfer function of the system from the output of the controller to the input of the controller. In [3], the CSI was expanded from a constant to a dynamic function with Laplacian variable s as shown in Figure 1.

The transfer function representing the dynamic performance of the power electronics and network can be derived as a Control Sensitivity Index CSI(s) using quasi

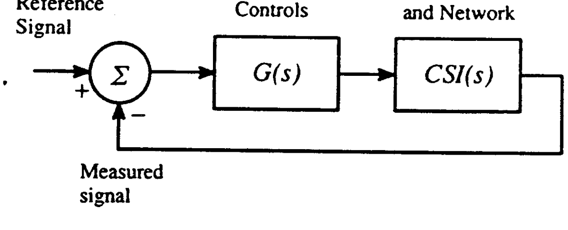


Figure 1 Representing controls and network as separate functions

steady state Jacobians [3],[2] or, by synthesis using an emtp simulation. Without diminishing the usefulness of the CSI formulation, use of the emtp determination of the power electronics and network transfer function is described herein. The emtp synthesis method is required when it is necessary to include the electromagnetic modes of the network in the transfer function. Subsynchronous or supersynchronous electromagnetic effects may need to be incorporated into the network transfer function for obvious reasons. As examples, consider the following real life electromagnetic mode network problems:

1) Applying SVC's to Series Compensated lines: A study on Hydro Quebec's 735 kV transmission network [4] exposed a shunt reactor resonance with series capacitors. The frequency of the oscillation could vary from a few Hz to 20 Hz and interact with the voltage regulator of an adjacent SVC in an undesirable manner.

2) SVC – HVdc – Ac System Interaction: The Quebec to New York State interconnection through the Chateauguay back–to–back dc link and SVC's was, under certain operating conditions, subject to a 2nd harmonic interaction. An innovative control system redesign overcame the problem which had led to substantial operating restrictions [5].

3) Nelson River HVdc 93 Hz Oscillation. During the commissioning of a 500 kV dc valve group of Manitoba Hydro's Bipole 2, a sustained 93 Hz oscillation was excited on several occasions which took several years to finally diagnose with the help of emtp simulation.

3. SYNTHESIZING THE NETWORK

Some power electronic controllers such as a static var compensator (SVC) can be tested in open loop as shown in Figure 2. Also shown is the location for signal injection into the firing angle regulator. The response to the injected signal can be observed as the measured voltage signal. By analysis in emtp of the injected signal and its response, the transfer function of the power electronics and the network can be determined in several ways. In the emtp simulation, the signal generator can inject either an impulse deviation of the ordered susceptance (0.2 to 1.0 per unit susceptance perturbation for 10 to 20 milliseconds), a step change, a spectrum of frequencies of equal magnitude from 1 Hz to perhaps 200 Hz simultaneously injected, a single frequency or a pseudo–random binary sequence noise signal.

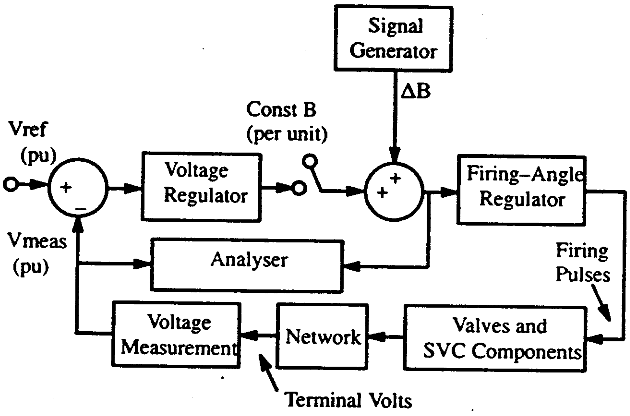
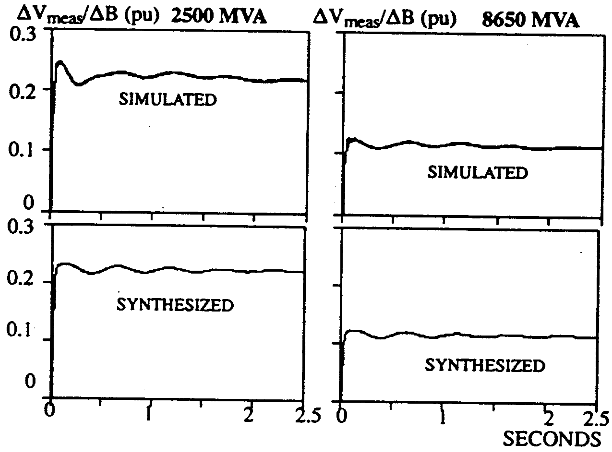


Figure 2 SVC and network in open loop with signal injection of incremental susceptance order ΔB

The easiest way to synthesize the power electronic converter of an SVC and the ac system network it is connected to is to inject a step change signal of susceptance to the input of the firing angle regulator as indicated in Figure 2. The measured ac voltage response V_{meas} will include all the dynamic effects of the ac system including other power electronic controllers, synchronous machines etc. in its proximity at a particular operating condition.

A study for the Canadian Electrical Association (CEA) on control coordination of fast acting voltage control devices [6] examined a 14 bus, 6 machine example power system with a dc link and an SVC in close electrical proximity to each other. The open loop test of Figure 2 with a step input to the SVC firing angle regulator produced the time domain responses for V_{meas} as a function of per unit susceptance is shown in Figure 3. Note that two different ac network configurations are examined in Figure 3, representing extremes in operating conditions at the terminals of the SVC. Included are a weak system where the short circuit capacity is 2500 MVA, and a strong system where the short circuit capacity is 8650 MVA. The network responses in Figure 3 inherently include the electromechanical effects of the synchronous machines as well as the electromagnetic effects of the ac system and the nearby dc link.



$$\Delta V_{meas} = \left[\frac{G1}{1+T1.S} + \frac{G2.S}{1+2\zeta S/\omega_0 + S^2/\omega_0^2}\right] e^{-T2.S}\,\Delta B$$

	G1	T1	G2	ζ	ω_0	T2
At 2500 MVA:	0.221	0.0087	0.0006	0.07	12.2	0.007
At 8650 MVA:	0.115	0.0111	0.0007	0.078	12.5	0.0088

Figure 3 Synthesized response of measured ac voltage ΔV_{meas} to a step change in SVC susceptance order ΔB (all in per unit)

Knowing the network response to the step input, a time domain function can be synthesized. There are several procedures available for synthesizing a time domain function. The method used here is a multi–variable Simplex optimization routine which fits a series of first and second order and delay functions to the known response with results as shown in Figure 3. The steps to the procedure are as follows:

1. Select an initial first or second order function which will approximate the known response. Include a delay function so that the first approximation is:

$$\frac{G_1}{\left(1 + sT_1\right)} \cdot e^{-sT_2} \qquad (1)$$

2. Inject the same step change input to the function selected in the first approximation (1) above as to the emtp open loop simulation of power electronics and network and optimize G_1, T_1 and T_2 to provide the best fit of output responses between the approximation (1) above and the emtp response.

3. Subtract the difference between the synthesized response to the step input to the approximation function (1) with the simulated emtp open loop response. Select an appropriate first or second order function which responds to the step input and by optimization again, approximate the response of the difference. In this SVC example, a suitable function to synthesize the difference was found to be:

$$\frac{s\ G_2}{\left(1 + 2\zeta s/\omega_0 + s^2/\omega_0^2\right)} \cdot e^{-sT_2} \qquad (2)$$

4. Repeat step 3 above until the difference is reduced to noise. Add the synthesized functions together as shown in Figure 3.

5. Repeat steps 1 to 4 for other operating conditions.

4. CONTROL DESIGN

With the power electronics and network synthesized to linear functions as depicted in Figure 3, it is possible to apply traditional control procedures to develop the voltage regulator to operate over the extremes of system operating conditions. The linearization of some power controllers, and SVC's in particular, is considerably enhanced by the inclusion of a linearizing design in the firing angle regulator as shown in Figure 4. Here a proportional–integral (P–I) controller as the voltage regulator sets the desired susceptance B in per unit for the SVC. The linearizer defines the number of capacitors of the thyristor switched capacitor (TSC) part of the SVC which must be in service and also the firing angle order input into the thyristor controlled reactor (TCR) part of the SVC. The P–I controller is designed for TCR operation.

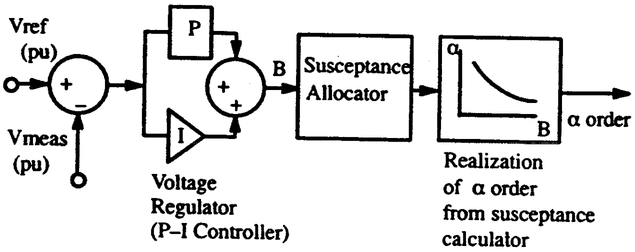


Figure 4. Linearizing an SVC controller to determine firing angle α_{order} from susceptance B defined by P–I control

With the linear functions synthesized for the most complex and most non–linear portion of the model as in Figure 3, a standard control design procedure can be applied for the determination of the gain and time constant for the P–I controller serving as the voltage regulator. Root locus, Nyquist or Bode control design methods can be applied.

Note that the delay function e^{-sT} will inherently be a part of any synthesized function involving power electronics and transmission lines. The most suitable linear function to use in its place for controls design is [3]:

$$e^{-sT} \approx \frac{\left(1 - sT/2\right)}{\left(1 + sT/2\right)} \qquad (3)$$

Suitable control parameters for the SVC voltage regulator are determined by the standard methods for each of the extremes of the operating conditions. In this example, the extreme operating conditions are represented by the low and high short circuit capacity in Figure 3. With the linearized model for the SVC and system, the best performance was determined to occur with the following settings for the P–I controller:

Table 1. Best settings for P–I controller for SVC voltage regulator using linear models

Short Circuit Capacity	*Gain for P*	*Time Const for I*
8650 MVA	*11.2*	*0.0022*
2250 MVA	*6.2*	*0.003*

5. NON–LINEAR CONTROL DESIGN

The real test comes when a large signal disturbance is applied to the SVC. A 2.5 cycle single line to ground fault was applied to the 500 kV bus to which the SVC is connected to through its transformer. The nearby dc link fails commutation when the fault is applied but recovers when the fault is cleared. The transformer of the SVC saturates after the fault clears. Now the non–linear effects of transformer saturation and dc link commutation failure and recovery are influential.

A procedure for determining the best setting for the P–I controller can no longer utilize the linearized control circuits. A simple experimental design procedure is to utilize the emtp simulation in a multiple run mode. A range over which the gain G of the proportional part of the voltage regulator can vary is specified, and in this case from 0 to 20 is designated. Similarly the range of the integrator time constant T is selected over 0.001 to 0.1 seconds. The input to the voltage regulator is per unit volts and its output is in per unit susceptance based on the SVC rating as per Figure 2. For each multiple run, the gain G and time constant T are selected randomly over the ranges specified. A performance indicator based on an integral square error of the difference between desired voltage for the SVC and the voltage measured, is used to select the best settings based on minimum error.

A contour plots of the results derived from all the multiple emtp runs for the identical fault with only G and T randomly selected for each run, are shown in Figure 5. The extreme cases with high and low short circuit capacity at the SVC are depicted. The S in each plot designates the values of G and T which produced the minimum error. The L in each plot defines the G and T which resulted in the largest error. The contour surrounding the S contains the 20% lowest errors of all the 50 runs of 1 second each. This contour provides an indication of the sensitivity of the settings for G and T. The **B** shown in Figure 5 is the best setting for G and T for the optimization exercise for the voltage regulator based on the linearized parameters of Figure 3.

After undertaking the design exercise based on linear models and review of the multiple run contours for large signal non–linear response, then a selection of a fixed setting for G and T can be made. Such an exercise is made on judgement rather than by mathematical optimization. In an actual design study, a larger number of operating contingencies and more large and small signal faults and disturbances would be undertaken to search for the best compromise settings of G and T.

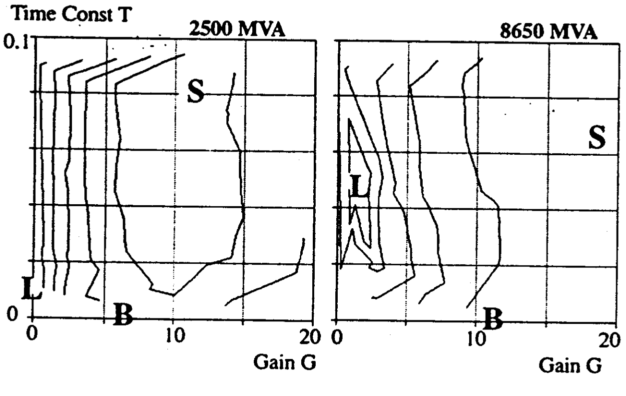


Figure 5 Multiple run contours for the P–I controller gain G and time constant T selection for the SVC voltage regulator based on a random search for best response

6. INTERACTION BETWEEN CONTROLLERS

The example power system in this case has a dc link and SVC in close electrical proximity to each other. In addition, there are synchronous machines with static exciters which also have the potential to interact with the fast responding controllers. The first step is to select the parameters whose perturbation or response will best indicate the performance of the devices under test. Suitable parameters for the SVC are:

(i) Measured ac volts input to the voltage regulator.
(ii) Firing angle order to the TCR.
(iii) A switching step of the TSC.

Suitable parameters for observing the dc link response are:

(i) Extinction angle (γ) at the inverter.
(ii) Firing angle (α) at the rectifier.
(iii) Measured dc current to the current regulator.

The control loops which define these SVC and dc link parameters are of concern in determining the sensitivity of interaction between the two fast acting controllers. A means of assessing the sensitivity of electromagnetic interactions between these high speed controllers is proposed.

7. GLOBAL GAIN MARGIN

The gain margin for the SVC is the factor by which the voltage regulator gain can be increased to drive it to the verge of instability. The ac system damping control on the dc link will also have its gain margin. A global gain margin is defined as a setting on a scale between 0 and 1 which causes the ac system to reach the verge of instability when the gains on all fast acting control devices are simultaneously adjusted such that at a setting of 0, the gains of all devices are at their nominal values and at a setting of 1, the gains of all devices are at their respective gain margin limits. The method of applying the Global Gain Margin test to the various high speed response controller devices in the simulated system is depicted in Figure 6. The multiple run parameter selector is varied graphically as the system is running in steady state until one fast acting device begins to exhibit steady state instability with one or more other devices.

When the global gain margin is 1 or near 1, there is little or no interaction between fast acting control devices. When the global gain margin is 0 or near 0, there is significant interaction between devices. For the test system and evaluating the interaction between the voltage regulator of the SVC and the ac damping controls of the dc link, the global gain margin for the low and high short circuit capacity systems are:

Global Gain Margin at 2500 MVA:	0.41
Global Gain Margin at 8650 MVA:	0.72

These results demonstrate that for this system under study, there is a greater risk of interaction between the dc

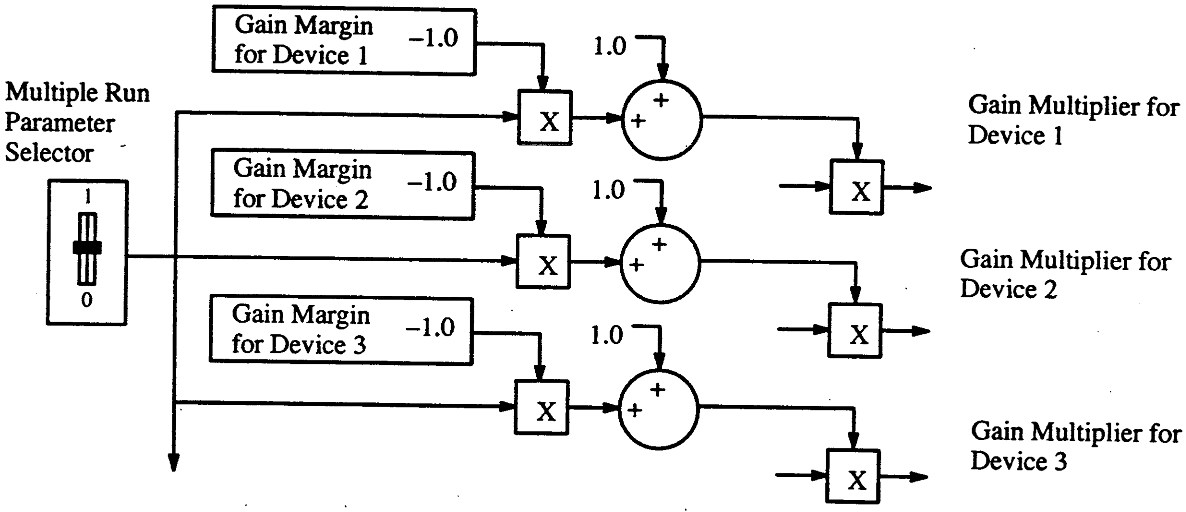


Figure 6. Determining Global Gain Margin through multiple run EMTDC simulations

link with its damping controls and the SVC with its voltage regulator at the low short circuit capacity than when operating on the system with the higher short circuit capacity.

Trial and error studies are one way to determine both the individual device gain margin and the global gain margin. If the emtp available has a multiple run capability with an automated parameter adjustment feature, then the gain margins can be determined computationally with minimum operator involvement. Electromagnetic transient studies are necessary to assess the gain margin since the frequencies of oscillation at onset of instability may be in the range 5 to 20 Hz or more and which cannot be precisely represented with phasor or algebraic network solution methods.

8. CONCLUSIONS

There is a significant role that electromagnetic transient programs can play in designing non–linear control systems in complex power systems. The increased computing power now available along with the increased sophistication and precision and speed available in modern emtp simulation programs provide the capability to undertake the design outlined herein.

The full scope of large power system non–linear controls design has hardly been touched by this paper. The use of Nyquist, Bode and root locus methods and deeper investigations into non–linear controls design methods needs to be pursued. Some specific contributions of this paper are:

- Modern electromagnetic transient programs can be applied to determine linearized, small signal representations of very complex systems, as well as provide a design tool for non–linear, large signal controls design. Phasor based simulation and solution methods cannot represent the non–linearities of transformer saturation and harmonic effects.
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- Control coordination studies and tests appear essential to prepare a system to operate at high transfer levels without a corresponding increase in risk.
- The design must consider the simultaneous interaction of all modulation signals and control systems to avoid unfavorable interactions among several fast controllers.

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