B4

HVDC Systems and Their Applications

Paper ID_10112

The Harmonic Loci-Based Control Design: Practical Methods in Frequency and Time Domain for a Consistent Design of VSC HVDC Harmonic Active Solutions

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Motivation

- VSC harmonic converter modelling considering the impact of control is under intense research to understand the converter behaviour itself.
- One important aspect is the detailed analysis of the impact of the AC network uncertainties in the harmonic converter design process which is the core of this publication.
- Two aspects to consider: harmonic performance and harmonic stability:
  - Typical performance uses the 50 years old Loci AC network representation method that covers AC network uncertainties (Figure 2).
  - The present stability analysis methodologies (in time and frequency domain) assumes that it will be possible to define a representative set of individual AC harmonic impedances for all operating conditions which is not practically possible.
- Another important issue is the time domain testability for high frequency resonances. The lack of simple time domain models to cover this part of the design is a concern at the time the final controllers are fully tested at the manufacturer's test facilities.

Method/Approach

- The two main proposed methods are:
  - A method to deal with both issues (performance and stability) in a unified manner by using the well-known loci-based analysis extended to the stability issues using Nyquist Analysis and associated concepts of phase margin (PM), gain margin (GM) and virtual margin (VM).
  - Simple synthetic AC network models to be used in time domain analysis able to reproduce single and double resonances based on AC network envelopes.
- The simplified process is summarized in Figure 1.

Objects of the investigation

- To present the theoretical and practical aspects of the "Loci-Based Control design" methodology:
  - The performance is presented in Figures 3,4,5 using equations (1) and (2).
  - The Loci stability approach is developed in Figures 6,7,8,9 using equations (3) and (4).
  - Synthetic models are presented in Figures 10,11,12.

Fig 1 Locus based control design process

Main Performance expressions (Fig. 3,4,5)

$$VP1(h) = \frac{Zn}{Zn+Zc}.Vc(h) = \frac{Yc}{Yn+Yc}.Vc(h) = k1(h).Vc(h) \qquad (1)$$

$$VP2(h) = \frac{Zc}{Zn+Zc}.Vn(h) = k2(h).Vn(h) \qquad (2)$$

Main Stability expressions for Nyquist Analysis (Fig. 6,7,8,9)

$$VP1(s) = \frac{Zn}{Zn+Zc}Vc(s) = \frac{1}{1+Zc/Zn}Vc(s) = \frac{1}{1+H}Vc(s) = k1.Vc(s) \qquad (3)$$

$$VP2(s) = \frac{Zc}{Zn+Zc}Vn(s) = \frac{Z_c/Z_n}{1+Z_c/Z_n}Vn(s) = \frac{H}{1+H}Vn(s) = \frac{1}{1+1/H}Vn(s) = k2.Vn(s) \qquad (4)$$

Where:
c is related to the converter harmonics (impedance and voltage)
n is related to the AC network harmonics(impedance and voltage)

Experimental setup & test results

A few examples of simulation calculations for performance and stability in frequency domain are presented in Figures 13 an 14.

Discussion

- Figures 13 and 14 are explained as follows:
  - Inputs: Zconv, Znet are respectively the converter impedances and network impedances for different frequencies.
  - Outputs: PM,GM,VM1,VM2 ,k1 and k2, where k1 and k1 are amplification factors defined in (1), (2),(3),(4).
  - PM and GM are not defined for all frequencies, see Fig.8.
  - $kmax \cong \frac{1}{\sin(PMmin)}$, in the most critcal cases.
  - VM1 and VM2 (virtual margins) are matematically defined as the inverse of maximum k1 and k2 in the complete frequency range. They are also defined graphically in Fig. 7 for a single condition.

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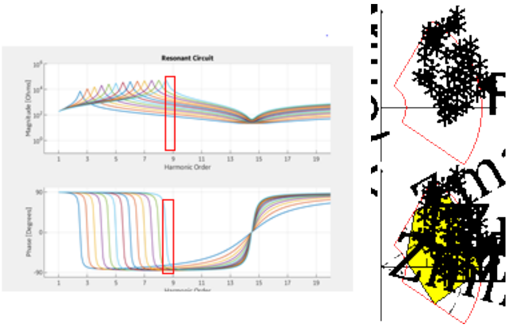


Fig 2 AC network Locus representation

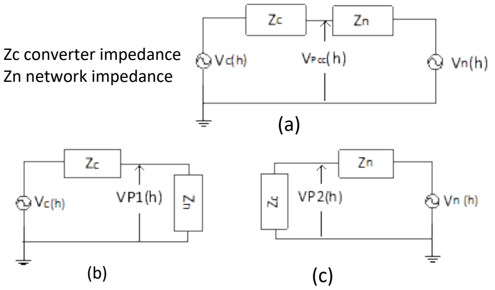

Zc converter impedance
Zn network impedance

Fig 3 Harmonic performance network model

Solution 3(b)

Solution 3(c)

Figs 4 and 5: Performance for 3(b) and 3(c)

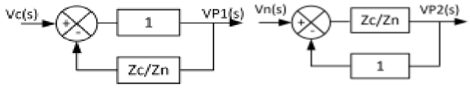
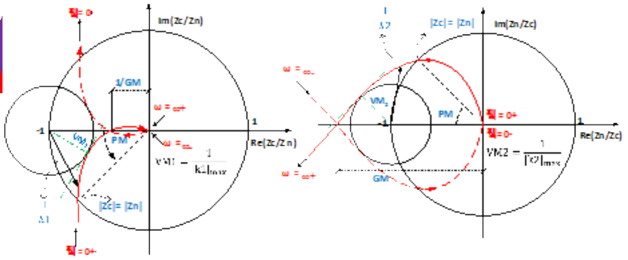


Fig 6 Circuits of Fig 3 (b) and 3(c) in close loop



$H_x(j\omega)$ plot

$1/H_x(j\omega)$ plot

Fig 7 Nyquist plots of Zc/Zn and Zn/Zc

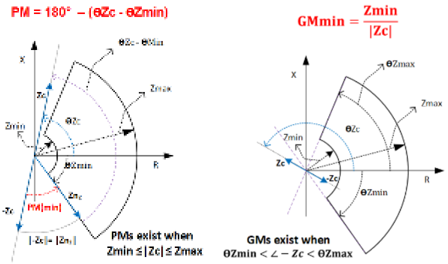


Fig 8 (a) and (b) – PM / GM in locus diagram

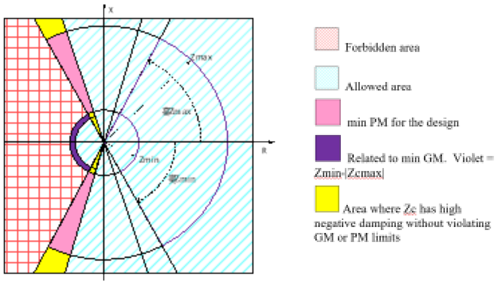


Fig 9 Forbidden and allowed areas for Zc

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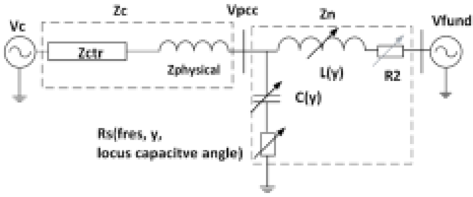
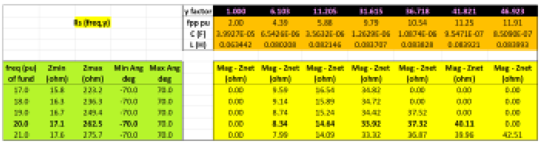
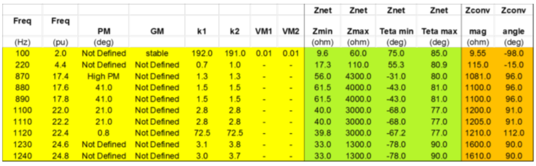


Fig 10 Synthetic Zn(y) model



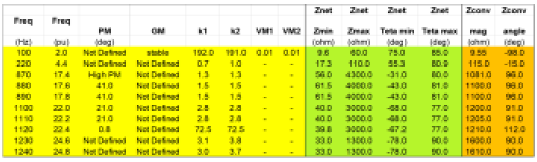
					y factor	1.000	6.103	11.205	31.615	36.718	41.821	46.923
		Rs (freq,y)			fpp pu	2.00	4.39	5.88	9.79	10.54	11.25	11.91
					C [F]	3.9937E-05	6.5426E-06	3.5632E-06	1.2629E-06	1.0874E-06	9.5471E-07	8.5090E-07
					L [H]	0.063442	0.080038	0.082146	0.083707	0.083828	0.083921	0.083993
freq (pu) of fund	Zmin (ohm)	Zmax (ohm)	Min Ang deg	Max Ang deg		Mag - Znet (ohm)	Mag - Znet (ohm)	Mag - Znet (ohm)	Mag - Znet (ohm)	Mag - Znet (ohm)	Mag - Znet (ohm)	Mag - Znet (ohm)
17.0	15.8	223.2	-70.0	70.0		0.00	9.59	16.54	34.82	0.00	0.00	0.00
18.0	16.3	236.3	-70.0	70.0		0.00	9.14	15.89	34.72	0.00	0.00	0.00
19.0	16.7	249.4	-70.0	70.0		0.00	8.74	15.24	34.42	37.52	0.00	0.00
20.0	17.1	262.5	-70.0	70.0		0.00	8.34	14.64	33.92	37.32	40.11	0.00
21.0	17.6	275.7	-70.0	70.0		0.00	7.99	14.09	33.32	36.87	38.96	42.51

Fig 12 Abacus of Rs f(L(Y),C(Y)), locus data



								Znet	Znet	Znet	Znet	Zconv	Zconv
Freq	Freq	PM	GM	k1	k2	VM1	VM2	Zmin	Zmax	Teta min	Teta max	mag	angle
(Hz)	(pu)	(deg)						(ohm)	(ohm)	(deg)	(deg)	(ohm)	(deg)
100	2.0	Not Defined	stable	192.0	191.0	0.01	0.01	9.6	60.0	75.0	85.0	9.55	-98.0
220	4.4	Not Defined	Not Defined	0.7	1.0	-	-	17.3	110.0	55.3	80.9	115.0	-15.0
870	17.4	High PM	Not Defined	1.3	1.3	-	-	56.0	4300.0	-31.0	80.0	1081.0	96.0
880	17.6	41.0	Not Defined	1.5	1.5	-	-	61.5	4000.0	-43.0	81.0	1100.0	96.0
890	17.8	41.0	Not Defined	1.5	1.5	-	-	61.5	4000.0	-43.0	81.0	1100.0	96.0
1100	22.0	21.0	Not Defined	2.8	2.8	-	-	40.0	3000.0	-68.0	77.0	1200.0	91.0
1110	22.2	21.0	Not Defined	2.8	2.8	-	-	40.0	3000.0	-68.0	77.0	1205.0	91.0
1120	22.4	0.8	Not Defined	72.5	72.5	-	-	39.8	3000.0	-67.2	77.0	1210.0	112.0
1230	24.6	Not Defined	Not Defined	3.1	3.8	-	-	33.0	1300.0	-78.0	90.0	1600.0	90.0
1240	24.8	Not Defined	Not Defined	3.0	3.7	-	-	33.0	1300.0	-78.0	90.0	1610.0	90.0

Fig 13 Example of calculation of k1,k2, PM,GM,VM1,VM2 using Locus (stable case)



								Znet	Znet	Znet	Znet	Zconv	Zconv
Freq	Freq	PM	GM	k1	k2	VM1	VM2	Zmin	Zmax	Teta min	Teta max	mag	angle
(Hz)	(pu)	(deg)						(ohm)	(ohm)	(deg)	(deg)	(ohm)	(deg)
100	2.0	Not Defined	stable	192.0	191.0	0.01	0.01	9.6	60.0	75.0	85.0	9.55	-98.0
220	4.4	Not Defined	Not Defined	0.7	1.0	-	-	17.3	110.0	55.3	80.9	115.0	-15.0
870	17.4	High PM	Not Defined	1.3	1.3	-	-	56.0	4300.0	-31.0	80.0	1081.0	96.0
880	17.6	41.0	Not Defined	1.5	1.5	-	-	61.5	4000.0	-43.0	81.0	1100.0	96.0
890	17.8	41.0	Not Defined	1.5	1.5	-	-	61.5	4000.0	-43.0	81.0	1100.0	96.0
1100	22.0	21.0	Not Defined	2.8	2.8	-	-	40.0	3000.0	-68.0	77.0	1200.0	91.0
1110	22.2	21.0	Not Defined	2.8	2.8	-	-	40.0	3000.0	-68.0	77.0	1205.0	91.0
1120	22.4	0.8	Not Defined	72.5	72.5	-	-	39.8	3000.0	-67.2	77.0	1210.0	112.0
1230	24.6	Not Defined	Not Defined	3.1	3.8	-	-	33.0	1300.0	-78.0	90.0	1600.0	90.0
1240	24.8	Not Defined	Not Defined	3.0	3.7	-	-	33.0	1300.0	-78.0	90.0	1610.0	90.0

Fig 14 Similar to Fig 13 (marginally stable case)

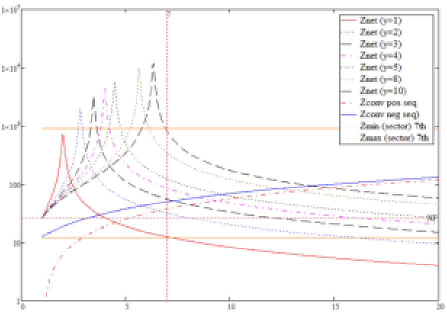


Fig 11 | Zc| and |Zn| synthetic networks

Conclusion

- The process of stability analysis using Loci is simple to follow and powerful.
- It will allow for the rapid verification of any intermediate control design in the harmonic range before going into more detailed time domain simulations.
- As the control design progresses, a more complete time domain simulation will be performed considering all non-linearities not included in the frequency domain evaluation.
- To test these systems, harmonic range synthetic time domain models may be available as soon as the loci are known representing the worst set of network configurations.
- The use of harmonic Loci-Based Control Design would allow a consistent agreement between manufacturer and clients during all stages of harmonic design processes including a full harmonic test at the final stages of the control delivery.
- The authors recognise the full complexity of transient responses taking into account non-linearities, interaction between controllers, etc., and the necessity to perform extensive analysis in complex hardware-in the-loop platforms; however, by using such simple methodology, they expect to make the harmonic control design targets more transparent in spite of the uncertainties existing in the design of VSC HVDC converters.