HIGH-FREQUENCY IMPEDANCE ESTIMATION AND EQUIVALENT WITH N4SID

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Abstract: This paper describes a Multiple Input Multiple Output (MIMO) System Identification technique for high-frequency impedance and admittance measurement. This technique uses a current or voltage white-noise source in the time domain and a generated linear state-space matrix in MATLAB™ environment. Part I of this paper presents a N4SID impedance validation with the classical frequency scan option in EMTP. This will be very useful when the user has FACTS models in his network and when FS cannot be used directly. In Part II, the admittance matrixes are calculated and the new state-space admittance power part is used in the time domain connected like a Norton Equivalent for a multiphase frequency-dependent network equivalent.

Keywords: Harmonic impedance, frequency scan, EMTP, state-space identification, N4SID, spectrum analysis.

ACRONYMS

BLW – baseline Wander

EMTP – electromagnetic transient program

FS – frequency scan

MIMO – multiple input multiple output

N4SID – numeric for system identification

SISO – single input single output

SO – system order

SV – singular value

THD – total harmonics distortion

I. INTRODUCTION

The frequency response of a transmission power system is an important characteristic for network analysis: suffice it to mention AC filter design and power quality studies. The frequency scan (FS) option currently in the Electro Magnetic Transient Program (EMTP) realizes these two actions: short circuit for voltages sources and open circuit for current sources. With the 1A fictitious current source placed by the user on the bus under study, all source frequencies are varied using the given frequency range, with the result that the network steady-state solution is found for each frequency [1].

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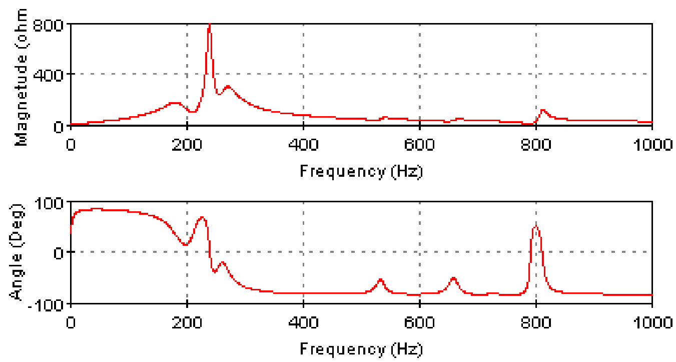
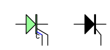


Figure 1 – Bus impedance calculation with EMTP FS option

This technique is quite appropriate for a network where all components are linear or passive and their matrices are invariant with voltage magnitude. However, the FS option cannot work properly when nonlinear or when switching devices like diode  or thyristor  are used on a large scale with FACTS equipment: DC line controller, static var compensator, thyristor-controlled series capacitor (TCSC), electrolytic load and, recently, the technology used by wind generators. This problem is not recent and is currently the focus of study for various researchers [6,7].

Live power measurement techniques, as spectrum analyzers, inject a pseudo random current source and measure voltage. The frequency response is calculated by means of U-I FFT mathematical operations [5]. The N4SID technique presented in this paper does not calculate FFT but takes advantage of one of the basic characteristics of power equipment: around U=1 p.u., their frequency responses can be considered linear. The N4SID technique gives the state-space matrix, which will be used for a Bode diagram, as seen in Figure 1. These mathematical routines [4] were recently used at IREQ for other linear phenomena: small-signal dynamic system identification [2,3] calibrated for a 0-5 Hz equivalent.

The main N4SID function takes the form:

$$[A,B,C,D] = subid(y,u,i) \qquad (1)$$

where

y: matrix of measured outputs

u: matrix of measured inputs

i: number of block rows in Hankel matrix, used to determine the size of matrix A, the system order(SO),

A,B,C,D: discrete state-space system.

In part I, outputs are voltages, inputs are currents and the state-space transfer function is the impedance. Part II describes how to obtain the admittance system. The new power state-space device [9] is subsequently used as a network equivalent in the time domain.

II. CURRENT SOURCE

The EMTP current source uses two components: a BaseLine Wander source (BLW) for random data streams and a controlled current source. They will be connected as shown below:

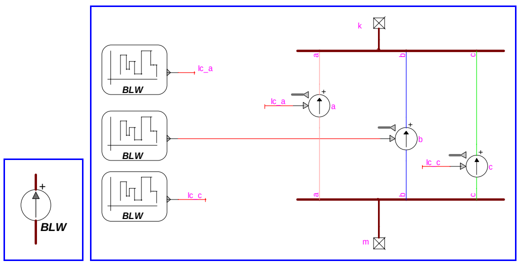


Figure 2 – Quasi-random current source in EMTPWorks, components (left) and inside (right)

The BLW subcircuit uses 14 control functions grouped in a Park and Miller minimal standard generator and a Box-Muller Transformation. The required sample rate, seed and covariance are given by the user. Note that the choice of sample rate has a direct effect on the energy's bandwidth spectrum. If the user is seeking the impedance identification range, either 5-500 Hz or 5-3000 Hz, the white-noise current spectrum has to be chosen correctly. The seed defines a particular random stream and the covariance changes the magnitude. Depending on the short-circuit level and the nominal voltage, the required white-source RMS current level must be set correctly to observe an adequate level of harmonics.

The currents and their energy spectrum are seen in Figure 3:

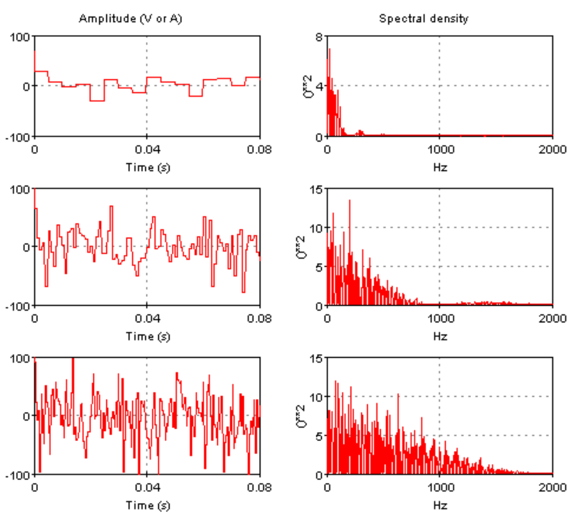


Figure 3. BWL random data streams with sample rate Ts =5000 (top), 1000 and 200 µs (bottom).

PART I

III. SINGLE-PHASE Z ID - SET THE N4SID USER'S PARAMETERS

Two other parameters must be calibrated in accordance with high-frequency network characteristics:

- minimum size of A matrix, the System Order (SO)
- minimum white-noise RMS current required observing the high-frequency voltages.

The first step of this work is to obtain a Single-Input Single-Output (SISO) identification validated for a 10-1000 Hz range. The relation we are looking for is:

$$Ua_{bus1} = [Z_a] * Ia_{blw} \qquad (2)$$

where Ia (A) is the input, Ua (V) the output, and Za (Ω) the transfer function.

Bus1 of the network230LFSM.ecf file in the EMTPWorks examples is chosen in this section. To evaluate the angle correctly, the polarity of input i_blw_1 and output U_bus1 is shown below.

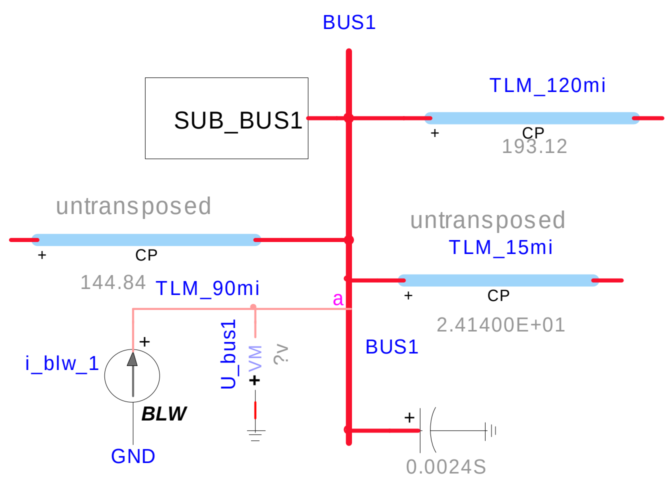


Figure 4. Single-phase impedance-identification setup.

The following parameters were chosen initially: sample rate set at 200 µs, the RMS current magnitude set at 25 A; the time simulation, 1 s.

The N4SID method gives the singular value (SV) for the energy evaluation of each order of the system. The first two points (Fig. 5) are equal to 8000 and they represent the fundamental frequency and others the high-frequency resonance in the transmission system. A first question to be asked is: how many poles do we need? Up to 5%, 1% or 0.1% energy of the first two points?

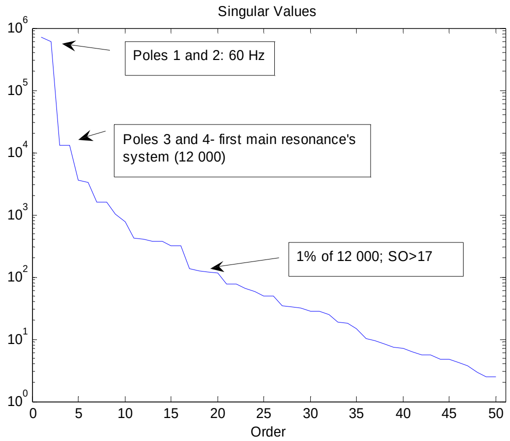


Figure 5. Singular values of the first 50 poles

The following figure compares the EMTP FS response with two identifications achieved with the system order (SO) set at 17 (<1%) and 10 (<6%).

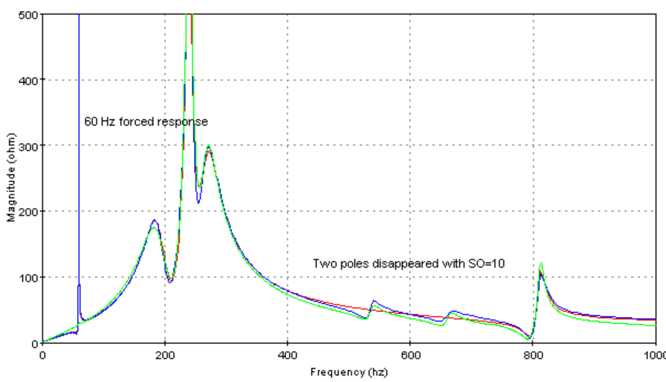


Figure 6 EMTP-FS (green) versus N4SID with SO=17 (blue) and =10 (red).

The matrices with SO=17 give a good fit and modes less than 1 kHz are well identified when compared with EMTP-FS. The n4sid technique shows a peak at 60 Hz, a non-existent resonance caused by the power plant's voltage. With SO=10, the Bode diagram shows two peaks disappeared. The rule of SV>1% used to set the number of poles offers good identification.

Another result helps the user in his choice of SO: the total harmonic distortion (THD) is defined by the difference between the EMTP time simulation outputs and the y(t) generated by the matrixes Za, the BLW current source being the input.

From SO>12, the lower number of poles has a direct impact on the THD; note a THD constant level around 0.5-0.6% no matter which system order is requested by the user.

SO	30	24	17	12	8	6
THD(%)	0,6	0,6	0,53	0,5	1,0	1,4

Table 1 - THD related to the system order.

Why? The error in the phase A voltage time is shown in Figure 7 with its Fast Fourier Transformation (FFT). This result is obtained with SO=17. The time error consists essentially of the fundamental and the third harmonic (180 Hz).

These differences are caused by nonlinearity in the time domain simulation, in this case a particular combination of the network third harmonic and the synchronous machine (SM) model.

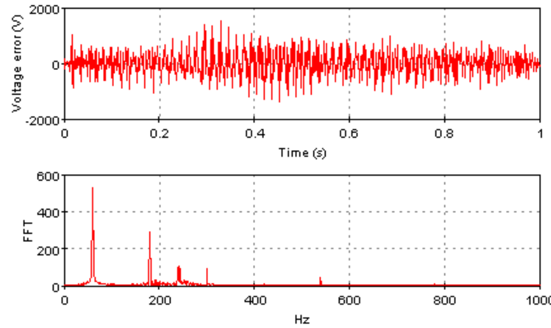


Figure 7 With Synchronous Machine model. A-voltage error, ID with SO=17, B - FFT voltage error

To verify the impact of the SM time model nonlinearity, we replace them by a fixed voltage source behind an impedance equal to X"d. In Figure 8, the identification was repeated and the harmonics in the errors disappear, confirming their nonlinear origin. This fact demonstrates that the identification error shown in Figure 7 is intrinsic to the non linearity of this particular frequency.

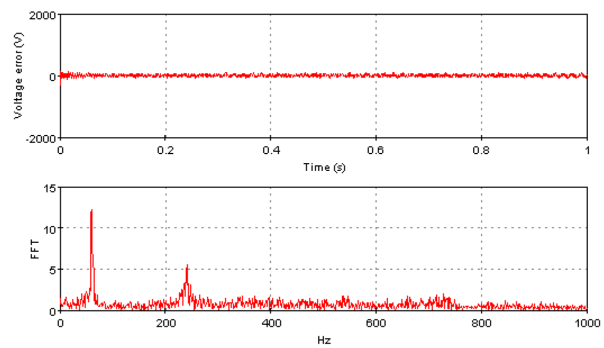


Figure 8. Without SM model (SO=17). A - voltage error; B – FFT voltage error

The last N4SID parameter to be set by the user is the minimum RMS current required to observe the poles. This value is related to certain characteristics of the nominal voltage and impedance.

I blw (ARMS)	40	25	15	10	5
THD(%)	0.5	0.5	0.63	2.3	5.0

Table 3 - THD related to the white-noise magnitude.

At 15 A and higher, the voltage spectrum has enough energy to allow good ID computation. Time simulation indicates that the short-circuit level equals 5.5 kA. Applied to a live network operating at U=1 p.u., the random current source RMS output must be higher than 0.5% of the network short-circuit level.

IV. Three-Phase Bus Z ID

The N4SID subid.m function is built for MIMO representation, an m-phase state-space system that can be unbalanced or not. The author used this functionality to synthesize a three-phase impedance matrix equivalent.

$$U_{abc} = [Z_{abc}sys] * I_{abc} \qquad (3)$$

It is essential that the three random-current sources differ from each other without a mathematical relationship. With I_{random} set to 25 A and a 1-s output data duration, the SV suggests an SO of 28, with the 1% rule. In Table 2, the relation THD versus SO confirms this value.

SO	46	36	28	24	18	14
THD	0,77	0,48	0,48	0,49	2,5	2,6

Table 2 - THD (%) related with the MIMO system order.

For each output, the FFT errors confirm whether the identification is adequate or not. Below output No. 1 is phase A.

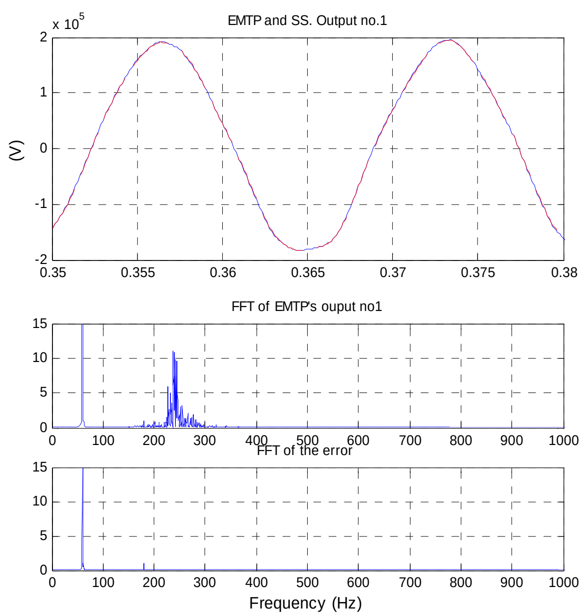


Figure 10. A-state-space output 1 superposed on EMTP output 1. B- FFT output and C - FFT error.

The ID quality could be checked with frequency scan (FS) EMTP results if available, as in this case. The transfer function between in1 and out1, 2 and 2, and 3 and 3 will be superimposed with Z_a, Z_b and Z_c from calculations with EMTP-FS up to 2 kHz.

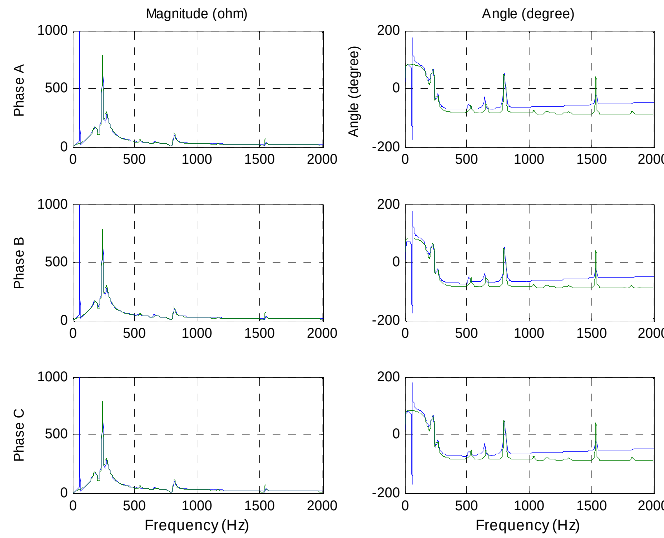


Figure 11. Bus phase impedance – FS (green) versus N4SID (blue).

ID validation will be done with Z_0, Z_1, and Z2 EMTP sequence calculations. To obtain the sequence matrices from $Z_{abc}sys$, we apply the transformation below:

$$Z_{012}sys = T^{-1} * Z_{abc}sys * T \qquad (4)$$

where $T = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$

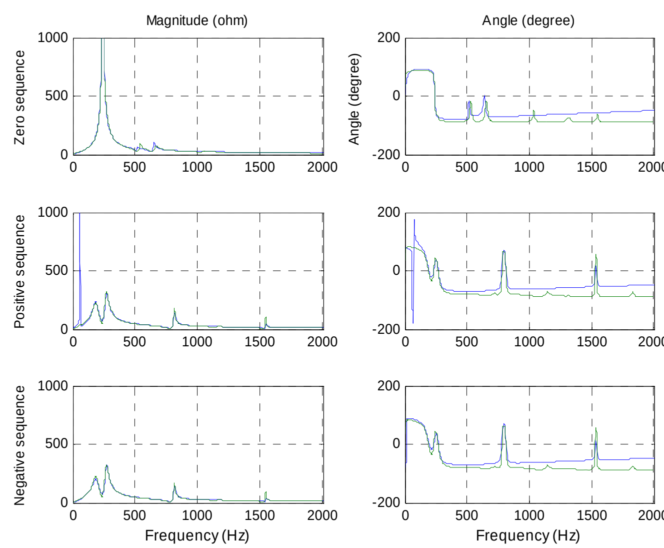


Figure 12. Bus sequence impedance – FS (green) versus N4SID (blue).

V. Two-Bus Identification

The N4SID technique can measure two bus frequencies in the same time and gives the coupling between the 6 phases. Note this subcircuit includes RLC component, CPline, transformer, synchronous machine and load, for a total of 1259 devices and 600 signals. In this example, the internal impedance of the two voltage sources is set at 1 MΩ.

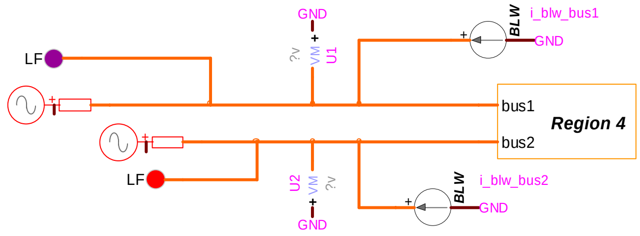


Figure 14 Six-phase identification setup.

The goal of this example is to obtain a 6 x 6 impedance equivalent with this equation:

$U1_{abc}U2_{abc} = [Zsys] * I1_{abc}I2_{abc}$ (5)

The best ID was achieved successfully with a sample rate equal to 100 µs, $I_{RMS} = 14$ A and 1 s time duration. The SO of the state-space matrix is set at 100. The THD is <2% between the ID and EMTP. In the time domain, the bus1-phase A (output No.1) and bus 2-phase A (output No.4) are shown in Figure 15. The FFT error indicates the smallest error that the state-space matrices introduce compared with EMTP.

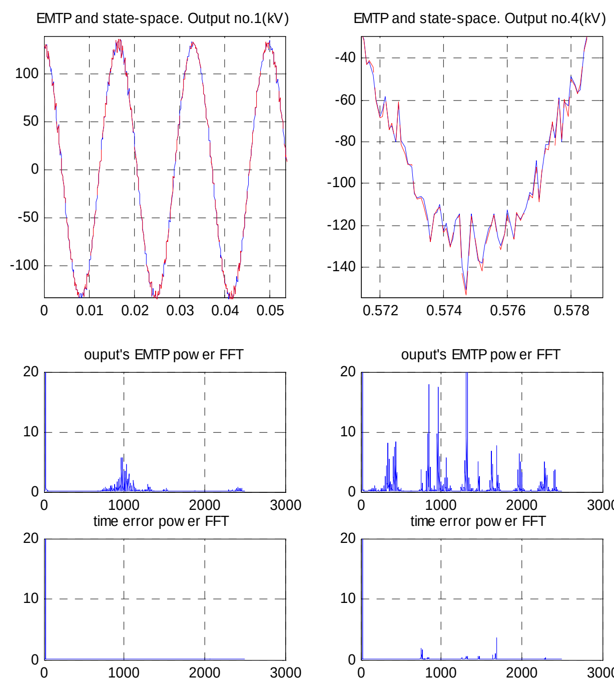


Figure 15. A- state-space output nos1, 4 superposed with EMTP. B-FFT's output and error for these outputs.

A 6 x 6 MIMO system had 36 transfer functions. Three of them are chosen for validation purposes in the frequency domain: bus1-Za, bus2-Za and the phase A impedance between the two buses. With the EMTP-FS option, these three impedances are calculated as follows:

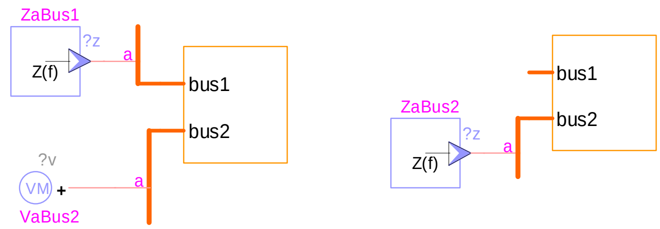


Figure 16. Frequency scan in EMTPWorks

According to the input-output definition of the state-space matrices, the phase A impedance between bus1 and bus2 is given by:

Za_bus1bus2 = Zsys(in,out) *where* in=1, out=4 (6)

In the frequency domain shown below, the fit is really impressive, from the point of view of the magnitude as much as the angle. Note yet the 60-Hz peak from the 1 p.u. voltage. These results demonstrate the capability of this N4SID method for impedance measurement, here up to 3 kHz.

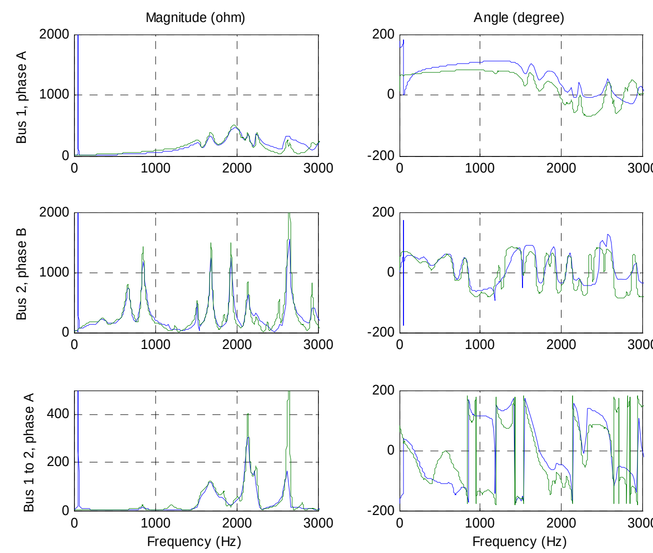


Figure 17 – EMTP-FS (blue) compared with the state-space (green). of the Bode diagram: left - magnitude; right – angle.

VI. THREE-PHASE TIES Z IDENTIFICATION

In this section, we introduce an application of this identification N4SID technique: the user measures a *section* of a passive or active network, as indicated in Figure 18. Two random source connections are possible:

- series voltage source with passive circuit (Region 1),
- shunt current source with active circuit (Region 3).

For an active circuit, a shunt current source gives better results and matrix conditionings. The U and I meters should be connected as in Figure 18, which has two benefits: 1) "fortunately" there is no 50-60 Hz pair of poles in the system matrices and 2) the relationship between URegion 3 vs

IRegion3 -Zsys (3) is independent of the frequency response characteristic of the main network. The polarity meters for current and voltage are also indicating.

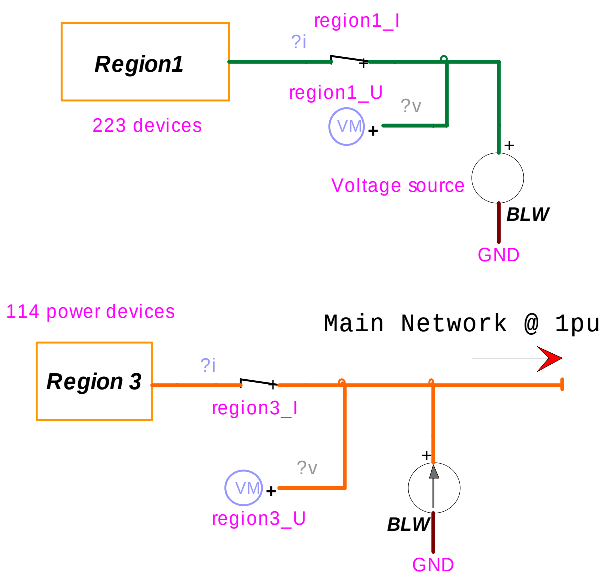


Figure 18. Two setup for ties identification.

For the active Region3 subcircuit, these results were obtained with SO=60. The THD is less than 0.2% and the correspondence with the theoretical FS is quite good.

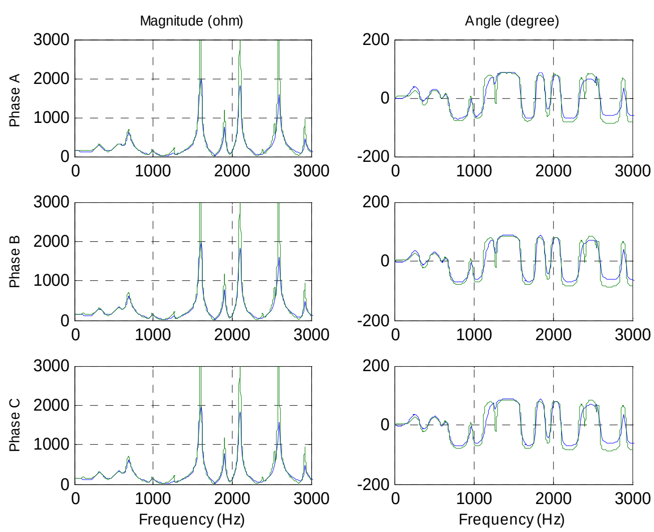


Figure 19. Ties phase impedance – FS (green) versus N4SID (blue).

PART II

VII. ADMITTANCE IDENTIFICATION

Replacing 100 network components by a linear equivalent is done essentially to save CPU computation time. The following approaches can be used:

1- Make an R-L-C parallel connection, one for each pole, connected in series. An analytical approach from the frequency scan results is applied to set the RLC values [8],

2- Use the new admittance state-space power component as shown in Figure 20.

An I_{Norton} or $U_{Thevenin}$ source (user's choice) is required if the user's subcircuit includes synchronous machines that contribute to the network short-circuit. The I_{Norton} source is set with the U in steady state and the Y_{60Hz} value. The $U_{thevenin}$, the internal voltage value, is calculated with U in steady-state and the PQ flow.

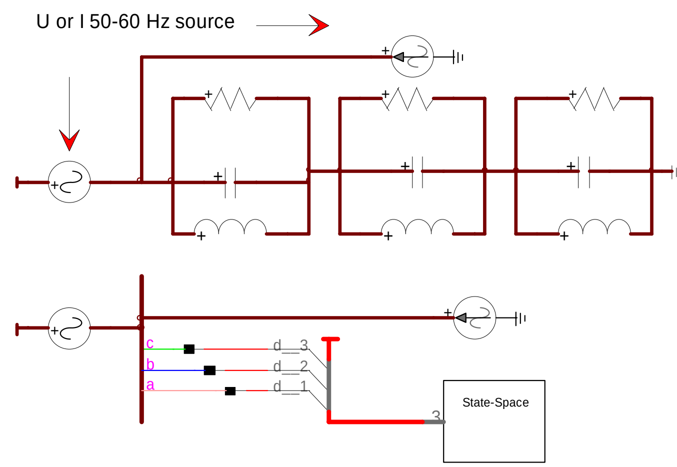


Figure 20 – Two 3-phase equivalent approaches

The new "state-space equations" component [9] is designed to provide the capability to use state-space equations for entering the generic relation between current and voltage of a given device. Note that obtaining the admittance Ysys with a mathematical inversion of previous Zsys does not work, as some Zsys zeros may have negative damping. So the n4sid method has to be used to identify these matrixes. The relationship reached is:

$$I_{abc} = [Y_{abc}sys] * U_{abc} \qquad (7)$$

VIII. THREE-PHASE TIES Y IDENTIFICATION

To replace a complete subcircuit by an admittance equivalent is a challenge, considering the importance of keeping the transients, 60 Hz up to a few kHz. A Region1 equivalent shown in Figure 18 is developed in this section.

The first validation of Region1 admittances is obtained when low THD results defined between EMTP and Ysys(t) are obtained in the time domain. A high system order (120) is also required to fit with THD=0.3%. The FFT of the time errors shows the low energy in the frequency domain up to 3 kHz.

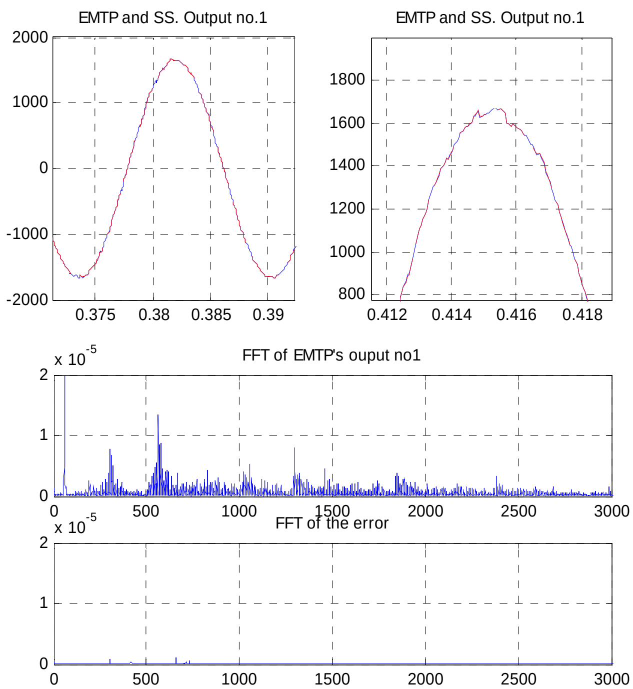


Figure 21 A and B - state-space output No.1 superposed with EMTP. C - error. D – FFT's error.

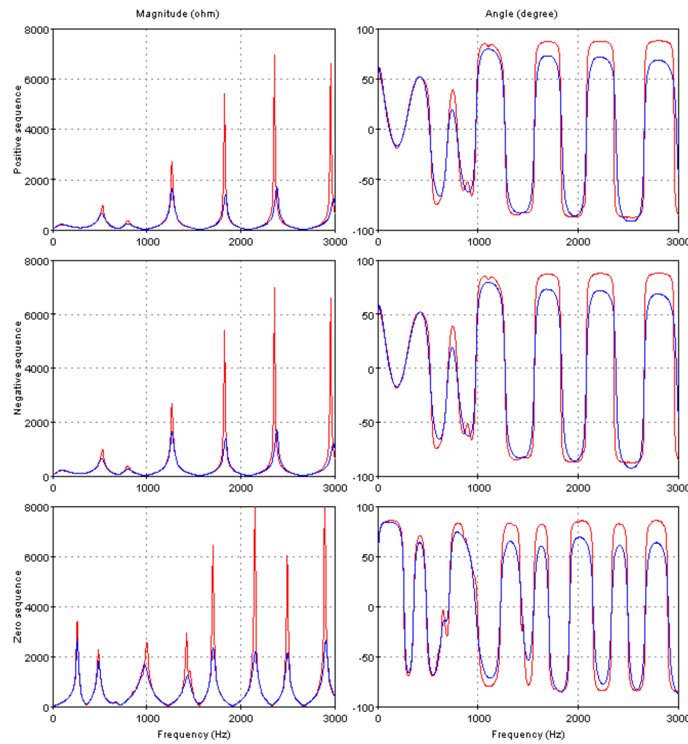


Figure 23 – Z1, Z2 and Z0 Bode diagram. SS power device (blue) compared with original subcircuit (red).

The second validation will be obtained with the FS option. The figure below shows how to compare the original subcircuit with Ysys that is required by the state-space power device. Two/three independent frequency scans were shown in Figure 22. Positive, negative and zero sequences are superposed in Figure 23.

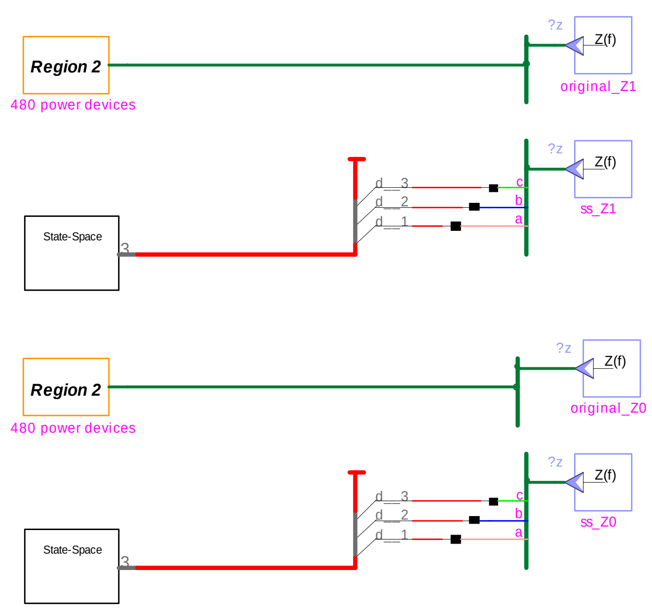


Figure 22 – Multiple FS setup with state-space device and a subcircuit

The last test required for final validation consists in a single-phase fault simulation with the state-space component and the full subcircuit and monitoring the current outputs. This type of fault is related to the zero- and direct-impedance signature. A fault schematic is presented below in Figure 23 and current and voltage plots in Figure 24.

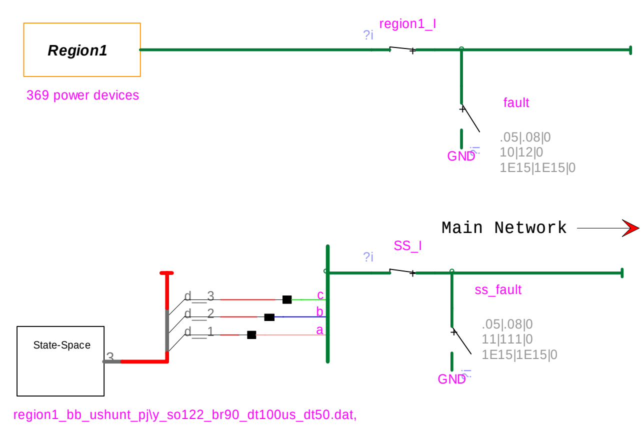


Figure 24 – Time simulation setup with a state-space device and a subcircuit

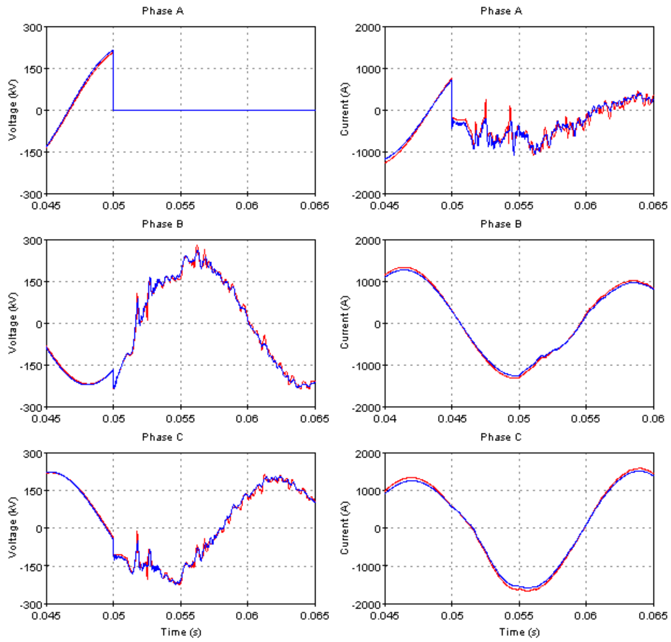


Figure 24 –Voltage and current outputs, original circuit (red) and state-space device (blue)

IX. CONCLUSION

FACTS technologies like windmills and industrial load are found more and more in transmission systems and the user EMTP files. Because the limitations of the frequency scan option for usefulness with linear circuit, this paper proposes an alternative: an identification technique for high-frequency impedance measurement based on a pseudo random source. This approach works both for a bus and tie.

X. ACKNOWLEDGMENTS

Thanks go to Luis-Daniel Bellomo, PhD student, École Polytechnique de Montréal for the BaseLine Wander random generator component in EMTPWorks.

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XII. BIOGRAPHIES

Luc Gérin-Lajoie received his BScA in Electrical Engineering from École Polytechnique de Montréal in 1982. From 1982 to 1985, he worked for Hydro-Québec in System Planning of the 120 kV network. He joined after, the Control and Protection team in the Systems Studies Department. His responsibilities include protection/automatism specification, modal analysis, optimization and control coordination, as well as electromagnetic phenomena and analytic studies related to the performance of SVC and synchronous machine on the bulk transmission system. He also contributed, for Hydro-Québec, to the validation of the new EMTP-RV and participates in the development of EMTPWorks models.

Innocent Kamwa (S'83, SM'98, F’05) received a PhD in electrical engineering from Laval University, Québec, Canada, 1988, after graduating in 1984 at the same university. Since then, he has been with the Hydro-Québec Research Institute, where he is at present a Principal Researcher with interests broadly in bulk system dynamic performance. Since 1990, he has held an associate professor position in Electrical Engineering at Laval University. A member of CIGRÉ, Dr. Kamwa is a recipient of the 1998 and 2003 IEEE PES Prize Paper Awards and is currently serving on the System Dynamic Performance Committee AdCom. He is also the acting Standard Coordinator of the PES Electric Machinery Committee.