Application of Passivity Enforcement in Power System Hybrid Simulation

QI GUO
China Southern Power Grid Technology Research Center

YIZHONG HU, WENCHUAN WU,
BOMING ZHANG
Tsinghua University China

SUMMARY

This paper presents an application of passivity enforcement in the electromagnetic transient (EMT)-transient stability analysis (TSA) hybrid simulation for power system. A passivity enforcement method based on perturbation of residue matrix eigenvalues has been implemented. This is for making the frequency dependent network equivalent (FDNE) passive to avoid unstable time domain simulations. The effect and necessity of FDNE’s passivity enforcement is demonstrated by numerical tests.

KEYWORDS

Electromagnetic transient - Frequency dependent network equivalent - Passivity enforcement - Power system simulation - Transient stability analysis
1. Introduction

China Southern Power Grid (CSG) is one of the largest parallel AC/DC transmission systems in the world, which contains the 'west-to-east transmission corridor' comprising eight 500 kV AC links, four ±500 kV DC links and two ±800kV HVDC links [1]. In such system, DC equipment is best modeled in an electromagnetic transient (EMT) program to simulate the power electronic devices accurately, while AC networks can be modeled in a transient stability analysis (TSA) program to assure efficiency for large scale system. Therefore, an EMT-TSA hybrid simulation platform has been developed.

In the EMT program, a network equivalent of the system modeled in the TSA program is needed to guarantee its precision [2]. Instead of using traditional Norton Equivalent which can only describe the fundamental frequency characteristics of the original network, a new equivalent strategy consisting of frequency dependent network equivalents (FDNE) and equivalent current sources, proposed by some researchers [3]-[4], has been used in our platform.

FDNE is actually an admittance matrix related to frequency, and it can be expressed by a rational function form, derived by vector fitting method [4]-[6]. Since an FDNE has the same concept as an admittance matrix, it has to be passive to guarantee the stability of hybrid simulation.

This paper analyses the application of passivity enforcement technology in our power system EMT-TSA hybrid transient simulation platform. First, the passivity of the FDNE used in the hybrid simulation is assessed by a half-size singularity test matrix [7], then passivity enforcement by perturbation of residue matrix eigenvalues [8] is implemented to make sure that the FDNE is passive. A representative test case is presented to prove that passivity enforcement is essential.

The remainder of this paper is organized as follows. Section 2 introduces the main idea of frequency dependent network equivalent. In Section 3, a method for assessment of FDNE’s passivity is presented. And a passivity enforcement method based on perturbation of residue matrix eigenvalues is realized in section 4. Numerical test studies are introduced in section introduces 5, and conclusions are stated in Section 6.

2. Frequency Dependent Network Equivalent

In brief, an FDNE is an admittance matrix dependent on frequency. It describes the relationship between port voltages \( u \) and currents \( i \) in a wide frequency band,

\[
i(s) = Y(s)u(s).
\]

FDNE can be expressed as

\[
Y(s) = \begin{bmatrix}
y_{11}(s) & y_{12}(s) & \cdots & y_{1N}(s) \\
y_{21}(s) & y_{22}(s) & \cdots & y_{2N}(s) \\
\vdots & \vdots & \ddots & \vdots \\
y_{N1}(s) & y_{N2}(s) & \cdots & y_{NN}(s)
\end{bmatrix},
\]

where \( s = j2\pi f \), \( f \) is frequency.

By means of vector fitting [4]-[6], every element can be obtained in a form of rational function as

\[
y(s) = \sum_{i=1}^{N} \frac{c_i}{s - a_i} + d,
\]

where poles \( a_i \) and residues \( c_i \) are real or complex conjugate pairs, \( d \) is real.

Then the \( Y(s) \) can be rewritten into an state-space form as

\[
Y(s) = C(sE - A)^{-1} B + D.
\]

Fig. 1 illustrates the equivalent strategy based on FDNE, which is almost the same form as Norton Equivalent, just replacing the admittance matrix with an FDNE to represent the frequency characteristics of the original network in wide-band.

3. Assessment of FNDE’s Passivity

The power consumed by the network represented by FDNE is

\[
P(s) = u \cdot G(s) \cdot u,
\]

\[
P(s) = u \cdot Y(s) \cdot u
\]
where \( u \) is the node voltages and \( G(s) \) is the real part of \( Y(s) \).

The passivity of FDNE means it can only consume energy in all frequency, theoretically. But in practice, we focus on a selected frequency range. Therefore, \( P(s) \) should be positive in the selected frequency range. That is, it must be guaranteed that \( G(s) \) is always positive definite, which equals to that all the eigenvalues of \( G(s) \) is positive, in this frequency range.

However, FDNE generated by vector fitting cannot satisfy the requirements mentioned above. In certain frequency bands, there may be some negative eigenvalues of \( G(s) \). And if you use this FDNE in the hybrid simulation, the result can be unstable.

Naturally, before the passivity enforcement, assessment of FDNE’s passivity has to be done. In other words, we have to find out in which frequency bands the FDNE is not passive. These frequency bands are so-called violating hands.

This paper use a half-size passivity test matrix \( P_m \) proposed by [7] to figure out the crossover frequencies,

\[
P_m = A \left( BD^{-1} C - A \right).
\]

The \( A, B, C \) and \( D \) in (6) are the same as (4). It has been proved that if the test matrix \( P_m \) has a positive eigenvalue \( \lambda_p \), then the crossover frequency \( \omega \) can be obtained by the equation

\[
\lambda_p = \omega^2.
\]

Moreover, it should be checked whether intervals partitioned by crossover frequencies are violating.

Take a simple case shown in Fig. 2 (quoted from [7]) as an example. It shows that \( G(s) \) ‘s eigenvalues \( \lambda_1, \lambda_2 \) have negative values in some frequency bands, and \( s_1, s_2, s_3, s_4 \) are the crossover frequencies. After checking every interval, we can get the violating band \( \{ s_1, s_4 \} \).

### 4. Enforcement of FNDE’s Passivity

After passivity assessment, this paper uses a passivity enforcement method based on perturbation of residue matrix eigenvalues proposed by reference [8]. The general idea of this method is to change the matrix \( C \) and \( D \) of (4) to assure the passivity, meanwhile minimize the corresponding change of \( Y \), expressed as

\[
\Delta Y = \sum_{m=1}^{n} \left( \frac{\Delta C_m}{s-a_m} \right) + \Delta D \equiv 0 \quad (a)
\]

subject to

\[
\begin{align*}
\text{eig}(\text{Re}(Y + \Delta Y)) &> 0 \\
\text{eig}(\text{Re}(D + \Delta D)) &> 0
\end{align*}
\]

One key point of this method is to perturb the eigenvalues of \( C \) and \( D \), rather than change the elements of \( C \) and \( D \) directly. So the independent variables in the problem are the variations of eigenvalues,
\[
\Delta x = \begin{bmatrix}
\Delta \lambda_{c_1} & \cdots & \Delta \lambda_{c_n} & \cdots & \Delta \lambda_{c_m} & \Delta \lambda_d
\end{bmatrix}.
\]

(9)

Then a lot of linearization processes have to be done in order to build up the relationships between other matrices and \(\Delta x\). The specific derivation process can be found in [8]. Representing \(\Delta C\) and \(\Delta D\) linearly by \(\Delta x\), using least square to describe the minimal change of \(Y\), (8a) can be rewritten as

\[
\min_{\Delta x} \frac{1}{2}(\Delta x^T A_{sys}^T A_{sys} \Delta x).
\]

(10)

Another feature to be pointed out in this method is the handling of (8b). The requirement that (8b) should hold in the entire selected frequency range makes it a tough problem. So we try to replace (8b) with some constraints at several particular frequency points. This is achieved by following steps, 1) regard \(G(s)\)’s eigenvalues as smooth functions and obtain the minimum points in the violating band; 2) insure the (8b) hold in the minimum points rather than in the entire violating band. This process is also demonstrated in Fig. 2, and \(M_1, M_2\) marked by red triangle are the minimum points. Thus, along with the linearization mentioned earlier, (8b) can be rewritten as

\[
B_{sys} \Delta x < 0.
\]

(11)

Finally the problem (8) can be transferred into a quadratic programming problem

\[
\min_{\Delta x} \frac{1}{2}(\Delta x^T A_{sys}^T A_{sys} \Delta x),
\]

\[st. \ B_{sys} \Delta x < 0\]

(12)

which can be properly solved by many optimization tools.

5. Application in Hybrid Simulation

In this section, the application of passivity enforcement in EMT-TSA hybrid transient simulation is detailed presented. The hybrid simulation platform we have developed is meant to simulate large scale AC/DC mixed power system. But a modified New England 39-bus pure AC system, shown in Fig. 3, is chosen as test system here, aiming at showing the effect and necessity of FDNE’s passivity enforcement.

More information about the hybrid simulation platform, including equivalent strategy and data exchange, can be found in [2].

The test system is divided into two parts, and the left part surrounded by dashed box (referred as EMT network) is modeled in the EMT program while the rest part (referred as TSA network) is modeled in the TSA program. An FDNE should be generated as an equivalent of the TSA network, embedded into the EMT program, as shown in Fig. 4. In this particular case, FDNE is a 6*6 matrix mathematically, because it’s two-port three-phase physically.

FDNE is used here to accurately describe the behavior of TSA network in a wide frequency range, which means that FDNE should have the same frequency responses as the original TSA network in this frequency range. This is exactly the advantage over admittance matrix and the reason why FDNE is implemented in the hybrid simulation.

Fig. 3. A modified New England 39-bus test system.

Fig. 4. The system simulated in EMT program.
Fig. 5 and Fig. 6 respectively illustrate the magnitude-frequency characteristics and phase-frequency characteristic of different kinds of FDNE’s one element, including

- Generated by vector fitting directly, marked as Raw FDNE;
- Processing the Raw FDNE with passivity enforcement method mentioned above, marked as Passive FDNE;
- As benchmark, not using any fitting techniques, measured from the original TSA network, marked as Original;
- In addition, calculating the deviation between Original and Raw FDNE, which is the error caused by vector fitting, marked as Error1;
- Calculating the deviation between Raw FDNE and Passive FDNE, which is the error caused by passivity enforcement, marked as Error2.

Fig. 5 and Fig. 6 clearly shows that both Raw FDNE and Passive FDNE are quite close to the Original, Error1 and Error2 are almost equal to zero. FDNE can represent the TSA network in wide frequency range indeed.

Raw FDNE and Passive FDNE’s all eigenvalues in a wide frequency range are illustrated in Fig. 7. (There should be totally six eigenvalues for each FDNE. It seems to be four because some of them overlap.) In the frequency around 2400 Hz, Raw FDNE has negative eigenvalues while Passive FDNE’s eigenvalues are always positive. Passivity enforcement adjusts negative eigenvalues in certain frequency bands indeed.

Now with different kinds of FDNE, a 100 ms three-phase grounded fault occurring in the bus 3 is simulated to prove the necessity of FDNE’s passivity enforcement. Specifically, this fault is simulated
in three methods,
- Using hybrid simulation with Raw FDNE, marked as Hybrid Simulation with Raw FDNE;
- Using hybrid simulation with Passive FDNE, marked as Hybrid Simulation with Passive FDNE;
- Modelling the entire system in the EMT program and simulating the fault, marked as Full EMT.

Fig. 8. Power delivered by transmission line 103-3.

As shown in Fig. 8, long before the fault occurring, Hybrid Simulation with Raw FDNE fails because it is numerically unstable in time domain. The power delivered by transmission line 103-3(on the bus #3 side), shown in Fig. 8, reflects the failure process expressly. Due to the fact that Raw FDNE is not passive, variables diverge with the iteration at the very beginning.

In the meantime, Hybrid Simulation with Passive FDNE achieves good results. Fig. 9 shows the simulation results of rotor speed of Generator #103 (the generator connected to bus #103). Hybrid Simulation with Passive FDNE is almost the same as Full EMT. Thus the necessity of FDNE’s passivity enforcement is sufficiently presented.

6. Conclusion
This paper presents the application of passivity enforcement in power system hybrid simulation, which is used to guarantee the passivity of the FDNE used in the EMT-TSA hybrid transient simulation platform. A half-size singularity test matrix is used to access FDNE’s passivity, and a perturbation of residue matrix eigenvalues based method is implemented to make the FDNE passive.

Through a modified New England 39-bus pure AC test system, the effect and necessity of FDNE’s passivity is clearly demonstrated.

7. References