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A Practical Exciter Model Reduction Approach For Power System Transient Stability Simulation

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Abstract

Explicit numerical integration methods for power system transient stability simulation require very small time steps to avoid numerical instability. The EXST1 exciter model is a primary source of fast dynamics in power system transients. In case of the EXST1, the required small integration time step for entire system simulation increases the computational demands in terms of running time and storage. This paper presents a practical exciter model reduction approach which allows the increase of the required step size and thus the method can decrease the computational demands. The fast dynamics in the original EXST1 are eliminated in the reduced exciter model. The use of a larger time step improves the computational efficiency. This paper describes the way to eliminate the fast dynamics from the original exciter model based on linear system theory. In order to validate the performance of the proposed method, case studies with the GSO-37 bus system are provided. Comparisons between the original and reduced models are made in simulation accuracy and critical clearing time.

Key Words : Power System Transient Stability Simulation, Explicit Numerical Integration Method, Numerical Integration Time Step, Computational Efficiency, Exciter Model Complexity Reduction, EXST1

1. Introduction

As modern power systems have been operated closer to their security limits, the importance of dynamic security assessment is increasing [1]. Power system transient stability analysis is a fundamental tool for the dynamic security assessment. It determines whether or not power systems will reach a new operating point and examines how system properties undergo transient deviations from an equilibrium following a disturbance [2-3]. Figure 1 a) shows a stable response and a system goes to a new steady state point. Conversely, in Fig. 1 b), a system becomes unstable before one can get a new operating point.

However, due to the large-scale nature of an interconnected power system and the nonlinear

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characteristics of power system equations, computational limits impose severe constraints for the power system transient stability simulation [4]. It is thus critically important to reduce the computational burdens; this has been an open challenge for many decades.

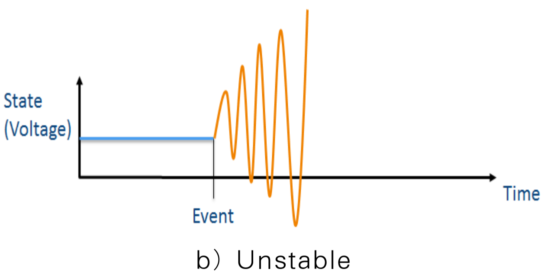

Fig. 1. Transient stability responses

Power system dynamics involve a wide variety of different time frames and they often have a great ratio between largest and smallest system eigenvalues, which is termed stiff. It ranges from microseconds to minutes, even to hours. Ordinary differential equations (ODEs) representing the power system dynamics can be solved by the use of numerical integration. Explicit numerical integration methods are widely used in commercial transient stability packages such as PSS/E, PowerWorld, and PSLF [5-7]. On a stiff power system, explicit numerical integration methods require very small time step to avoid numerical instability. If the time step is too large, numerical instability might happen. In practical power systems, only a small fraction of system states show very fast dynamics. Thus, it is inefficient to simulate the entire system with the small time steps.

Exciters are mainly used to control a generator terminal voltage and the reactive dynamics. They usually show a much faster response than any other components in power system transient stability simulations. For example, in the Western Electric Coordinating Council (WECC) system, the EXST1 exciter model (IEEE Type ST1 excitation system model) [8], the most common exciter in the system, introduces real part eigenvalue less than -2600, which is extremely fast varying response. Thus, for the use of explicit numerical integration methods, careful consideration should be made to prevent numerical instability issues and very small time steps are required. This increases the required computations for transient stability simulation.

The author presented a condition-based exciter model reduction approach that dynamically switches between the original EXST1 exciter model and the reduced one, depending on the system conditions [9]. In this paper, a practical simplified approach is presented to improve computational efficiency and extend the reduced model usage by considering critical clearing time as a transient stability index. This approach replaces the EXST1 exciter with the reduced EXST1 where the fast mode in the original model is eliminated. Thus a larger time step can be used without any numerical stability problems and significant computational benefits can be achieved. This paper describes how to remove the high negative eigenvalue from the original exciter model based on linear system theory. It also investigates the simulation accuracy with the reduced one.

This paper is organized as follows. A brief explanation about explicit numerical integration method is presented in Section 2. Section 3 begins with problem definition with EXST1 exciter model and a practical exciter model reduction method is proposed. Section 4 illustrates simulation results with GSO 37-bus case. The conclusion is made in Section 5.

2. RK2 Explicit Numerical Integration

Explicit numerical integration methods estimate next time step values explicitly with present values. The second-order Runge-Kutta (RK2) method is one example of the explicit methods and is the main numerical integration scheme for PowerWorld simulator [6]. With an ODE $\dot{x}=f(x,t)$, the RK2 method approximates next time step value with the following form [10].

$$x_{n+1}=x_n+\frac{h}{2}(k_1+k_2) \qquad (1)$$

where $k_1=f(x_n,t_n)$ and $k_2=f(x_n+k_1,t_n+h)$
h : numerical integration time step

The region of stability with the RK2 method is defined with (2) and is depicted in Fig. 2.

$$\left|1+h\lambda+\frac{1}{2}(h\lambda)^2\right|<1 \qquad (2)$$

where λ is a system eigenvalue.

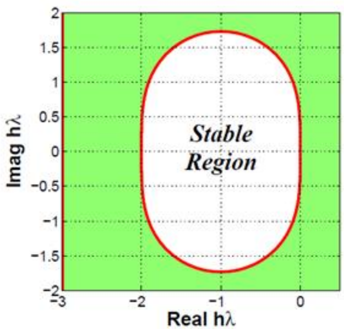

Fig. 2. Region of stability of the RK2

Based on the region of stability in Fig. 2, the required time step for a system with minimum eigenvalue -2400 should be smaller than 0.05 cycles which are 0.00083 seconds. Power system transient stability simulation repeats every time step until the simulation time reaches its end time. The use of the very small time step multiplies the number of repetition and thus results in the significant computational expenses.

3. Proposed approach

3.1 Problem definition

The exciter model is used to control a machine terminal voltage and the reactive power dynamics and it is the primary source of fast dynamics [2]. With the WECC system considered for this study, many generators show real-part eigenvalues less than -1000 and thus a very small numerical integration time step is required. Table 1 shows a few smallest eigenvalues from SMIB (Single Machine Infinite Bus) analysis, which identifies system eigenvalues with a simple system modeling a machine in detail and representing the rest of the system with a Thevenin equivalent [3]. As shown in Table 1, all the exciters are the EXST1 model. If the very fast modes can be eliminated from the EXST1 exciter model, a larger simulation time step can be used without numerical instability. This can allow users to improve the computational efficiency.

3.2 EXST1 model and the reduction

A block diagram of the EXST1 exciter model is shown in Fig. 3. The differential feedback block brings about a very big negative eigenvalue in the closed-loop transfer function. When two lead-lag compensators are neglected for simplification, the overall closed-loop transfer function is described in (3).

Table 1. SMIB eigenvalues of the WECC system

Bus Number	Exciter Model	Min. Eigenvalue
A	EXST1	-2601.8
B	EXST1	-2101.7
C	EXST1	-2101.7
D	EXST1	-1477.3
E	EXST1	-1422.9
F	EXST1	-1316.3
G	EXST1	-1277.9

$$T(s) = \frac{V_A}{V_{REF} + V_S - V_1} = \frac{K_A(1+sT_F)}{T_A T_F s^2 + (T_A + T_F + K_A K_F)s + 1} = \frac{K_A(1+sT_F)}{T_A T_F (s-p_1)(s-p_2)} \quad (3)$$

where p is the root of denominator and $p_1 \ll p_2 < 0$

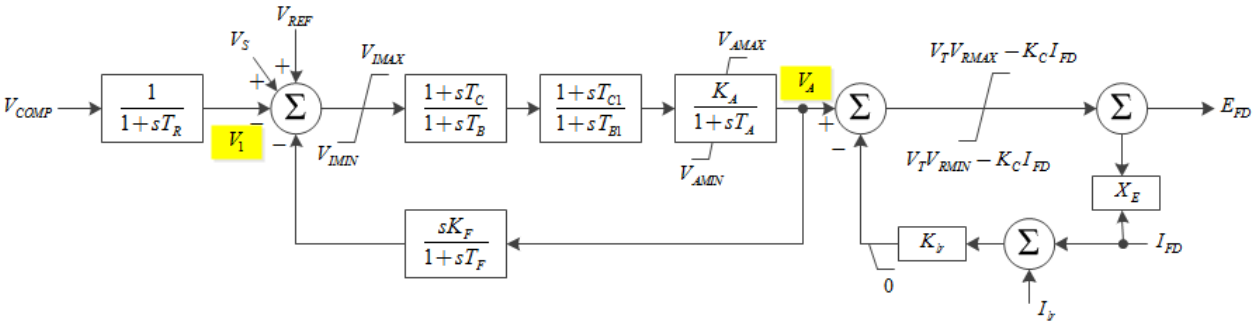

Fig. 3. Block diagram of EXST1 exciter model [8]

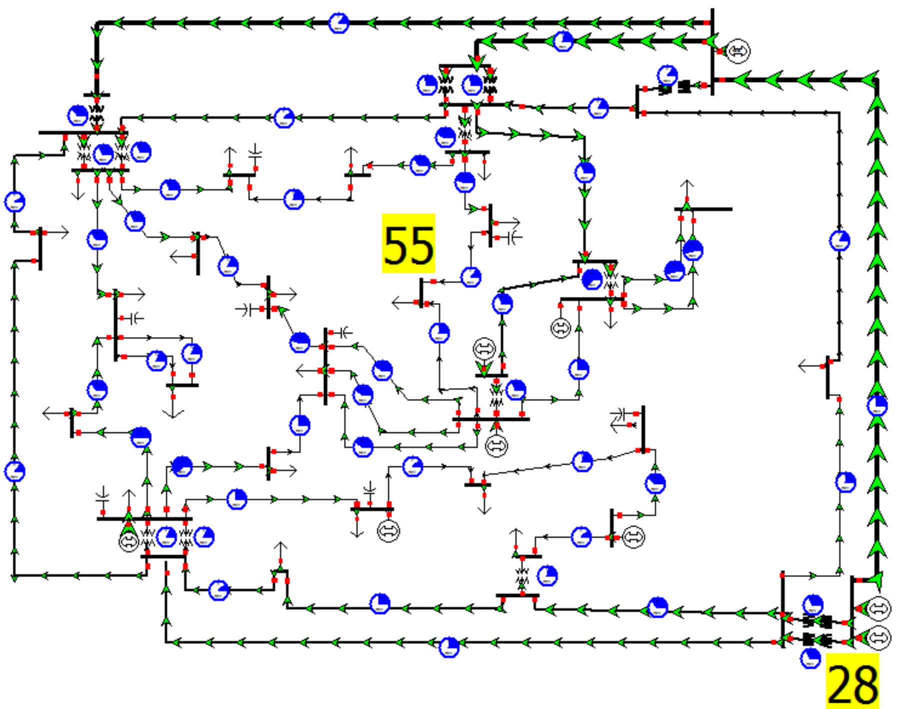

Fig. 4. GSO-37bus system [11]

$$T_{reduction} = \frac{K_A(1+sT_F)}{T_A T_F(-p_1)(s-p_2)} \quad (4)$$
$$= \frac{K_A(1+sT_F)}{T_A T_F(-p_1)(-p_2)(1-p_2/s)}$$
$$= \frac{K_A(1+sT_F)}{(1-p_2/s)}$$

where $T_A T_F(-p_1)(-p_2) = 1$ from equation (3)

When the fast eigenvalue(p_1) is eliminated from the closed-loop transfer function in (3), the reduced transfer function can be derived in (4).

The proposed approach is to use the reduced EXST1 exciter model instead of the original model. Then, the larger time step can be used without numerical instability issues and without significant loss of simulation accuracy. The reduced transfer function can be simply implemented by changing the parameters of the EXST1 model.

4. Case study

Case studies were carried out with the GSO-37 bus case shown in Fig. 4 in order to validate the performance of the proposed method. The GSO-37 bus system consists of nine generators, 25 loads and 57 branches [11]. The generator and controller dynamic models including governor and exciter are compiled in Table 2. Additional system information including power flows, transmission line impedances, and dynamic model parameters can be found in [12]. For test purposes, parameters of the two EXST1 exciters at bus 28 were set as shown in Table 3 such that each exciter is associated with a big negative eigenvalue, -2102. The closed loop transfer function is shown in (5) and it can be understood how the very big negative eigenvalues are originated from the exciters. PowerWorld simulator was used for all the simulations.

Table 2. Dynamic model information for case studies

Bus #	ID #	GEN Model	Governor Model	Exciter Model
14	1	GENROU	GAST	IEEET1
28	1	GENROU	HYGOV	EXST1
28	2	GENROU	HYGOV	EXST1
31	1	GENSAL	IEEEG1	EXST1
44	1	GENSAL	TGOV1	EXDC1
48	1	GENROU	TGOV1	IEEET1
50	1	GENROU	GAST	EXST4B
53	1	GENROU	TGOV1	IEEET1
54	1	GENROU	TGOV1	IEEET1

Table 3. EXST1 exciter parameters

Tr=0	Vimax=10	Vimin=-10	Tc=1
Tb=1	Ka=200	Ta=0.01	Vrmax=3.6
Vrmin=0	Kc=0	Kf=0.04	Tf=0.4
Tc1=1	Tb1=1	Vamax=99	Vamin=-99
Xe=0	Ilr=0	Klr=0	

The performance of the proposed method is evaluated by comparing simulation results using the original EXST1 model with using the reduced model. The reduced EXST1 model was realized by changing the parameters of the original exciter model as described in Table 4. All the limiters of the original model shown in Fig. 3 are preserved in the reduced model. The reduced model provides the exact same eigenvalue (-0.12) except the eliminated one.

$$T(s) = \frac{V_A}{V_{REF}+V_S-V_1} \quad (5)$$
$$= \frac{200(1+s0.4)}{0.004s^2+8.41s+1}$$
$$= \frac{200(1+s0.4)}{0.004(s+2102.4)(s+0.12)}$$

$$T_{reduction}(s) = \frac{V_A}{V_{REF} + V_S - V_1} \quad (6)$$
$$= \frac{200(1+s0.4)}{0.004(2102.4)(s+0.12)}$$
$$= \frac{200(1+s0.4)}{(1+s/0.12)}$$

Table 4. Reduced EXST1 exciter parameters

Tr=0	Vimax=10	Vimin=-10	Tc=1
Tb=1	Ka=200	Ta=0	Vrmax=3.6
Vrmin=0	Kc=0	Kf=0	Tf=1
Tc1=0.4	Tb1=8.41	Vamax=99	Vamin=-99
Xe=0	Ilr=0	Klr=0	

Three different faults are applied to consider various conditions depending on fault type and electrical distance. First, two different fault types are tested, which are the generator outage at bus 28 and the bus to ground fault at 55. In addition, the bus to ground faults at bus 28 is tested to take into consideration of electrical distance.

4.1 Simulation accuracy comparison

First, generator ID1 at bus 28 had an outage at 1 second. Figure 5 shows bus voltage magnitude at bus 28, the real and reactive power output of generator ID2 at bus 28. The simulation results with the original EXST1 are completely identical to those with the reduced one.

For the next comparison, a three-phase bus to ground fault was applied at bus 55 at 1 second and the fault is cleared at 1.1 second. Figure 6 shows the simulation comparisons. As shown in the figures, all the dynamic responses between the original and the reduced models are the same and the differences cannot be identified on the simulation outcomes.

At last, when a three-phase bus to ground fault happens at 1 second at bus 28 and it is cleared at 1.05 seconds, the dynamic responses are depicted in Fig. 7. The simulation differences are obvious, especially in reactive power responses. The exciter function is closely related to the reactive power dynamics. The reduced model where the high frequency pole was already removed brought about the differences on the responses. Compared to other types of faults, only the three-phase fault at bus 55 made the differences on simulation comparisons. This can be understood that the abrupt voltage deviation at bus 28 from the fault excites the high frequency mode (-2102 in the original exciter model), but the reduced model fails to maintain the response from the high frequency mode.

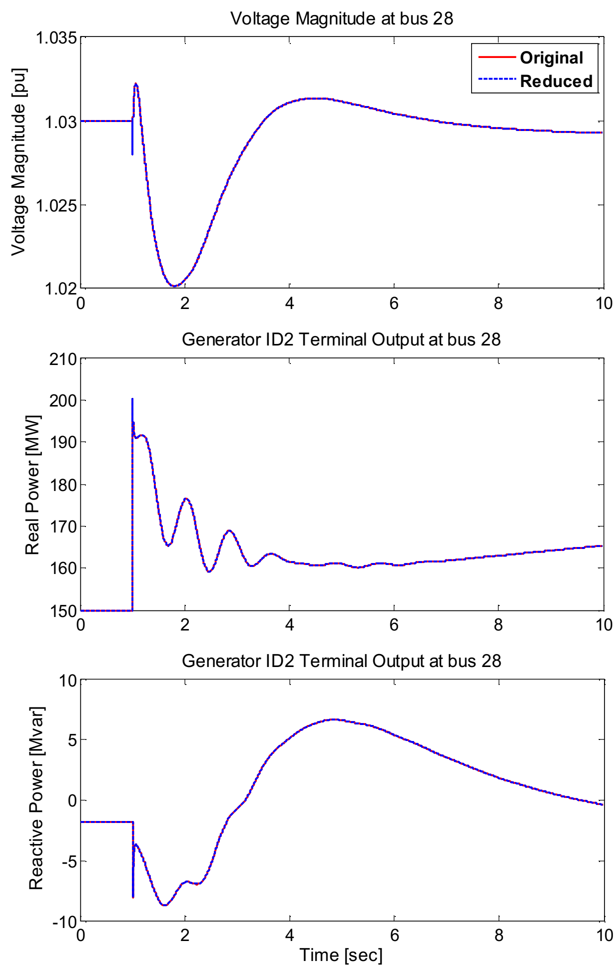

Fig. 5. Simulation comparisons with Gen ID2 outage at bus 28

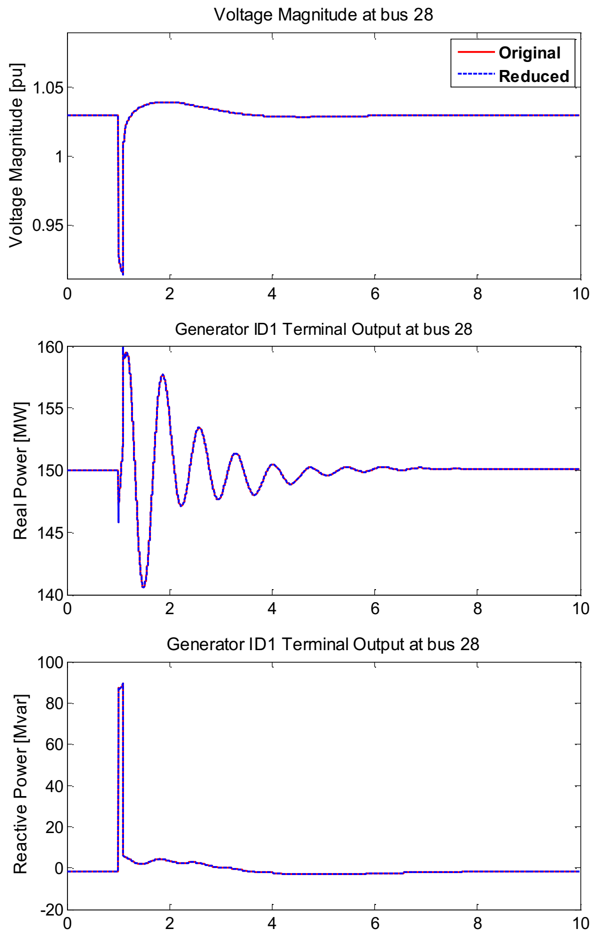

Fig. 6. Simulation comparisons with the bus to ground fault at bus 55

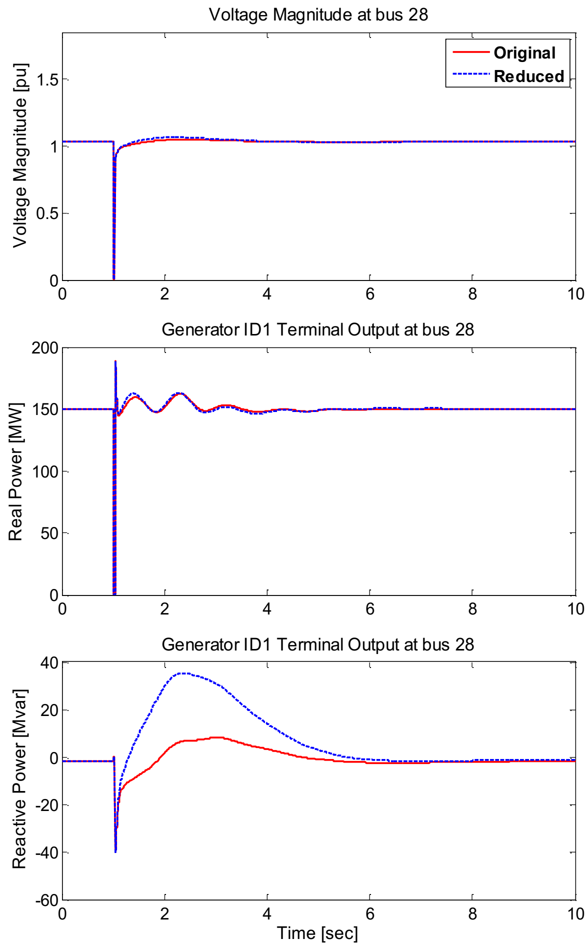

Fig. 7. Simulation comparisons with the bus to ground fault at bus 28

With the comparisons in Fig. 7, it should be noted that both responses go to the same stable operating points. In this regard, one more simulation comparison was made with the bus to ground fault at bus 28, which made a slight difference in the responses. Critical clearing time (CCT) [11] between using the original EXST1 model and the reduced one is compared to investigate if the use of the reduced exciter model can provide correct transient stability information. The CCT is the maximum fault duration for which a power system remains stable. It was measured by increasing the fault duration until losing the system stability. The bus to ground fault at bus 28 was applied at 1 second and both systems lost their system stability if the fault was not cleared before 1.5 seconds. Thus as shown in Table 5, the CCTs (0.5 second) for both systems are exactly same. It can be understood that the reduced model can provide same transient stability information.

Table 5. Comparison of Critical Clearing Time

Fault Type	Original Model	Reduced Model
Bus to ground fault at bus 28	0.5 second	0.5 second

4.2 Simulation time comparison

Table 6 shows the computation time and maximum time step for transient stability simulation with the GSO-37 bus system. When the bus to ground fault at bus 55 is applied at 1 second, the simulation is run to 10 seconds. The computation time is an average of 10 times simulation with an Intel 2.7GHz Pentium processor. The proposed method shows excellent computational performance by reducing the simulation time about 98%. This significant computational benefit could be obtained by increasing the simulation time step to 2 cycles from 0.05 cycles. However, in practical power systems, the time step cannot be increased as in this case study because other fast dynamics (commonly around -500) originate from the power system dynamic models. Therefore, a quarter cycle is a common simulation time step for the U.S. power grid.

Table 6. Computation time comparison

Exciter model	Time Step (Cycle)	Time to Solve (sec)
Original	0.05	47.99
Reduced	2.4	1.08

5. Conclusion

In this paper, a reduced exciter model approach has been explored. The approach utilizes the reduced EXST1 exciter model instead of the original EXST1 which commonly introduces very fast dynamics to power systems. The use of the reduced model allows one to increase a simulation time step without numerical stability issues and thus the method can improve computational performance. From the case studies with the GSO-37 bus system, the reduced model approach can give an advanced transient stability method, which provides a fast solution of about 98%, while maintaining the high level of simulation accuracy in terms of the transient responses and CCTs. It is expected that this practical approach would be a promising solution for difficulties in solving power systems with very fast dynamics.

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Biography

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Soobae Kim received the B.S degree in electrical and computer engineering from Kyungpook National University, Daegu, Korea, in 2002, the M.S. degree from Seoul National University, Seoul, Korea, in 2004, and the Ph.D. degree from the University of Illinois at Urbana-Champaign, Urbana, IL, USA, in 2014. Since 2004, he has been with Korea Electric Power Research Institute (KEPRI), Daejeon, Korea. His special fields of interest are power system analysis, dynamic system equivalent, and model reduction.