The Improved SSR Electromagnetic Simulation Model and Its Comparison with Field Measurements

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Keywords: Subsynchronous Resonance, Electromagnetic Simulation, Series Compensation.

Abstract: Electromagnetic simulation (EMS) plays an important role in the evaluation of subsynchronous resonance (SSR). To meet the requirement of practical engineering, this paper discusses how to improve the modeling method of SSR-EMS in three important aspects, i.e., the shaft system of turbine generator, the series compensation and the supplementary excitation damping controller (SEDC). Thus a systematically improved EMS model was put forward, which includes a lumped mass-spring model with adjustable and non-linear mechanical damping, a series compensation model incorporating MOV with the gap protection logic and an engineering model of SEDC to reflect the dynamics of the power-electronic exciter. The developed model overcomes the shortage of the traditional one and is applicable to the accurate analysis on SSR stability, transient torque and fatigue expenditure when the system experiences large disturbances. The proposed method is then used for the simulation of a real SSR event caused by a short-circuit fault in the Shangdu series-compensated power system. The simulation results are compared with the field measurements and a good consistence is found. Consequently, the improved EMS model is proved to be applicable, accurate and effective for SSR analysis in practical engineering.

1 INTRODUCTION

With the wide application of series compensation in power systems, the SSR issue attracts more and more attentions (SSR W.G., 1992). SSR analysis plays an important role in evaluating its risks and selecting countermeasures. Currently, such methods as frequency-scanning, complex torque coefficient, eigenvalue analysis and electromagnetic simulation (EMS) are widely applied (Yu et al., 2006; Canay, 1982; Hara et al., 1994). Among these methods, the time-domain EMS, despite of its complicated modeling and heavy computation, possesses obvious advantages as follows:

1) Capable of modeling system nonlinearities;

2) Applicable to the analysis of multi-mode torsional oscillation in multi-machine systems;

3) Able to analyze either large or small disturbances, and to provide dynamic response and output in the sense of electromagnetic transients;

4) Suitable for the evaluation of various SSR-damping devices, such as the supplementary excitation damping control (SEDC).

Therefore, EMS becomes an indispensible tool for SSR analysis in engineering application. Currently, this analysis method is mainly depend on commercial software like PSCAD/EMTDC (Kajoijilertsakul et al., 2011), which can provide the basic models and numerical method required by SSR analysis and meet the general analysis demand. However, there are some problems requiring attention and improvement. To meet the requirement of practical engineering, this paper mainly focuses on the modeling improvement in three aspects:

1) The mechanical damping of the T-G shaft system, assumed in many studies to be a fixed value, should be modeled as a function of the T-G's working condition (Xie and Zhang et al., 2011).

2) The nonlinearities of the metal oxide varistor (MOV), the gap and other protective devices should be incorporated for accurate modeling of a real-world series compensation.

3) The power-electronic circuit of the excitation system is regarded as an "instantly" established circuit during electromechanical transients. However, there is a time-delay, which will affect the dynamics

Xie X., Dong Y., Bai K., Gao X. and Liu P..
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DOI: 10.5220/0003973704190424
In *Proceedings of the 2nd International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2012), pages 419-424
ISBN: 978-989-8565-20-4

of exciter-based SEDC control system, thus making it necessary to refine its modeling.

This paper attaches great emphasis on the modeling improvement in the mentioned aspects, and applies it in a real electric network, i.e., the Shangdu series-compensated power system. Then, EMS results are compared with the actually recorded data to prove its accuracy, applicability and efficiency of the improved simulation method.

2 THE IMPROVED MASS-SPRING SHAFT MODEL OF THE TURBINE-GENERATOR

For SSR evaluation, a turbine-generator (T-G) is represented as a lumped mass-spring model (IEEE Committee report, 1977, 1985; Baker et al., 2005). For instance, the widely used 600MW T-G in China is expressed by a 4-mass spring model, as in Figure 1. It has 4 rotors, i.e., a high-and-intermediate-pressure turbine (HIP), two low-pressure turbines (LPA/LPB), and a generator rotor.

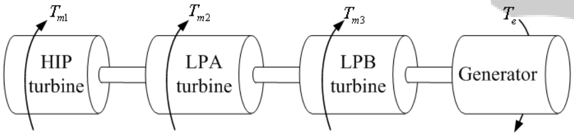

Figure 1: The lumped T-G shaft system.

Representing the T-G as inertias connected by shafts of appropriate stiffness, the dynamic equation for the spring-mass system may be written as (1)

$$\boldsymbol{M}\ddot{\boldsymbol{\delta}} + \boldsymbol{D}\dot{\boldsymbol{\delta}} + \boldsymbol{K}\boldsymbol{\delta} = \boldsymbol{T}_{\mathrm{m}} - \boldsymbol{T}_{\mathrm{e}} \quad (1)$$

Where: $\boldsymbol{\delta}$ is the torsional angle displacements column matrix; $\boldsymbol{M}$ is a diagonal matrix representing the inertias of masses; $\boldsymbol{D}$ is the damping coefficient matrix; $\boldsymbol{K}$ is a tri-diagonal matrix of torsional stiffness; $\boldsymbol{T}_m$, $\boldsymbol{T}_e$ are vectors of mechanical and electrical torques respectively.

Model (1) is widely adopted in EMS softwares like PSCAD/EMTDC. However, it has several drawbacks in practice: The damping matrix $\boldsymbol{D}$ can neither be provided by the manufacturer nor be measured through test directly. Actually it is a nonlinear function of system condition and cannot be interpreted by model (1). But in PSCAD/EMTDC, its value can only be set fixed rather than self-adjustable. As a result, when operating status changes, it is impossible to achieve accurate EMS.

Model (1) is improved in view of these shortages. Specifically, implement model decoupling transformation to model (1). That is, have $\boldsymbol{\delta} = \boldsymbol{Q}\boldsymbol{\delta}_{\mathrm{m}}$, and have equation (1) left multiplied by $\boldsymbol{Q}^{\mathrm{T}}$, where the model decoupling matrix $\boldsymbol{Q}$ is the right eigenvector of $\boldsymbol{M}^{-1}\boldsymbol{K}$. Then, model (1) can be transformed into the canonical form as (2):

$$\boldsymbol{M}_{\mathrm{m}}\ddot{\boldsymbol{\delta}}_{\mathrm{m}} + \boldsymbol{D}_{\mathrm{m}}\dot{\boldsymbol{\delta}}_{\mathrm{m}} + \boldsymbol{K}_{\mathrm{m}}\boldsymbol{\delta}_{\mathrm{m}} = \Delta\boldsymbol{T}_{\mathrm{m}} \quad (2)$$

Where $\boldsymbol{\delta} = \boldsymbol{Q}\boldsymbol{\delta}_{\mathrm{m}}$, $\Delta\boldsymbol{T}_{\mathrm{m}} = \boldsymbol{Q}^{\mathrm{T}}(\boldsymbol{T}_{\mathrm{m}} - \boldsymbol{T}_{\mathrm{e}})$, $\boldsymbol{M}_{\mathrm{m}} = \boldsymbol{Q}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{Q}$, $\boldsymbol{K}_{\mathrm{m}} = \boldsymbol{Q}^{\mathrm{T}}\boldsymbol{K}\boldsymbol{Q}$, $\boldsymbol{D}_{\mathrm{m}} = \boldsymbol{Q}^{\mathrm{T}}\boldsymbol{D}\boldsymbol{Q}$.

In model (2), although the coefficient matrices $\boldsymbol{M}_{\mathrm{m}}$ and $\boldsymbol{K}_{\mathrm{m}}$ are decoupled into diagonal matrices, it is still impossible for the damping coefficient matrix $\boldsymbol{D}_{\mathrm{m}}$ to achieve complete decoupling since it is not a diagonal matrix. However, as the coupling damping between modes is usually assumed to be small and can be almost contained within the damping of each mode, the non-diagonal elements of $\boldsymbol{D}_{\mathrm{m}}$ are ignored. This means to have $\boldsymbol{D}_{\mathrm{m}} \approx \boldsymbol{D}_{\mathrm{md}} = \mathrm{diag}\{d_{m1},\ d_{m2},\ d_{m3},\ 0\}$ (where 0 represents the damping of electromechanical mode), thus realizing the decoupling among torsional modes. So each natural mode is governed by an equation of the form:

$$M_{\mathrm{m}k}\ddot{\delta}_{\mathrm{m}k} + d_{\mathrm{m}k}\dot{\delta}_{\mathrm{m}k} + K_{\mathrm{m}k}\delta_{\mathrm{m}k} = \Delta T_{\mathrm{m}k},\ k = 1, \ldots, N \quad (3)$$

where the subscript k denotes each of the decoupled torsional modes.

Compared with model (1), model (3) is advantageous in achieving decoupling of torsional mode, and replacing the complicated $\boldsymbol{D}_{\mathrm{m}}$ with modal damping d_m, which can be measurable via various methods, e.g., the excitation-injection test and the system-side disturbance test. Furthermore, it is possible to set d_m as a nonlinear function of generator variables and to simulate its actual variation with the constantly changing system conditions in EMS. According to our actual measurements, the modal mechanical damping can be expressed by the non-linear function:

$$d_{\mathrm{m}} = \alpha_{\mathrm{m0}}\,\mathrm{e}^{\beta_{\mathrm{m0}}\cdot\Delta\omega_{\mathrm{m}}} + k_{\mathrm{m}}P + c_{\mathrm{m0}} \quad (4)$$

Where $\Delta\omega_{\mathrm{m}}$ is the modal speed deviation, P is the power of the unit, and α_{m0}, β_{m0}, k_{m}, c_{m0} are coefficients, which can be determined with a method like that proposed in literatures (Xie and Zhang et al., 2011).

3 THE IMPROVED MODEL OF SERIES COMPENSATION

The fixed series compensation (FSC), as shown in Figure 1, consists of series capacitor banks and corresponding protection devices such as MOV, current-limiting damping elements, protective gap and by-pass switch. MOV and the protective gap, though exert no impact on SSR stability during small disturbances, have significant impact on the transient torque, especially during the fault occurrence and a period of time after the fault. Therefore, it is necessary for EMS to take the nonlinear characteristics of MOV, the protective gap and the by-pass switch into account, especially when there’s a need to analyze the transient torque and the consequent fatigue expenditure of the generator shaft following large disturbances. Figure 3 is the improved modelling of FSC in our EMS method, among which:

1) MOV is expressed by the series circuit composed of controllable voltage source and non-linear resistance. Its V-I characteristic is described with an external file.

2) The protective gap and the by-pass switch are replaced by an ideal switch with specific logic of protection to simulate MOV’s various protective actions: a delayed monostable trigger signal is output when the current or the energy of MOV exceeds the set value, and thus the switch for controlling the ideal by-pass is turned on for a set time period and then turned off again.

The FSC model in Figure 2 is able to simulate the general actual logic of the practical series capacitor as well as its protective circuit when experiencing large disturbances. Since the energy exchange between the series capacitor and the generator determines the SSR dynamic, especially the transient torque of the shaft, this model can accurately reflect the actual dynamics of FSC.

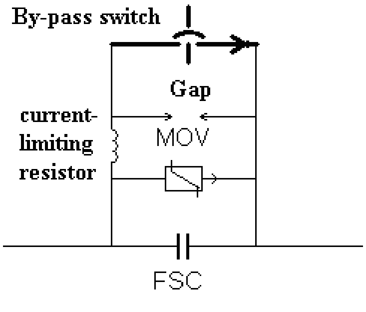

Figure 2: Schematic of FSC.

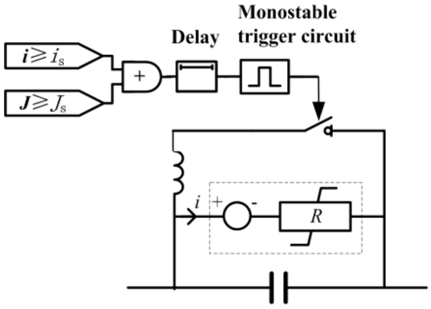

Figure 3: Electromagnetic model of FSC.

4 THE ELECTROMAGNETIC MODEL OF SEDC

SEDC is a real-time control system that works through the excitation system by modulating the field voltage at torsional frequencies. Figure 4 illustrates the relationship of the SEDC (Xie and Guo et al., 2011), the excitation regulator, the generators and the grid. As a supplementary control, SEDC uses the mechanical speed of the HIP turbine (ω_1) to generate the subsynchronous control output (u_{SEDC}). However, the well-established electromechanical transient model of the excitation system cannot be applied directly in SSR-EMS, because the control frequency (300Hz) of the thyristor in the power-electronic circuit, i.e., the three-phase fully-bridge controlled rectifier bridge, is much higher than that of DC and low-frequency components, on which the electromechanical transient analysis focuses. In other words, it is reasonable to ignore the dynamics of the power-electronic circuit in electromechanic analysis and regard it as an ideal “algebraic” converter. But in SSR-EMS, the dynamic characteristics of the power-electronic exciter must be considered because the torsional frequencies (generally from 10 to 40Hz) and the control frequency of thyristor are comparable.

Based on tests on the exciters of large generators, a refined EMS model of the excitation system with SEDC is proposed, as shown in Figure 4, in which, the power-electronic circuit of the exciter is expressed by a first-order-plus-time-delay transfer function. The dead time delay (T_d) represents the computational delay of the control law and the transport delay of the thyristor, while the first-order function is used to approximate the dynamics of the power-electronic circuit. Although T_d, T_r, generally from several to a dozen milliseconds, are very small compared with electromechanical transients, they are comparable with the period of torsional modes and thus have significant impact on the tuning of SEDC parameters.

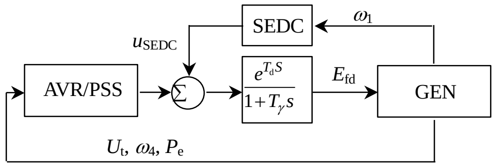

Figure 4: EMS model of the SEDC and excitation system.

5 VERIFICATION OF THE IMPROVED MODEL

The improved EMS model proposed above has been applied in many practical SSR studies. Here a short-circuit fault that occurred in a real system is used to verify its effectiveness.

5.1 The Shangdu System

Shangdu Power Plant (SPP) is located in Inner Mongolia Autonomous Region, about 300km north of Beijing. It has four 600MW turbine-generators connected to North China Power Grid through 500 kV lines, as shown in Figure 5. To improve transfer capability and system stability, FSCs are applied to the two lines between SPP and Chengde substation with 45% compensation degree. Each turbine-generator consists of four rotors, as shown in Figure 1, resulting in three torsional modes, of which the frequencies (in Hz) are listed in Table 1. Previous study indicated that the generator suffered serious SSR if one of the two Shangdu-Chengde lines is switched off for any reason (Xie and Guo et al., 2011). Thus SEDC and torsional stress relay (TSR) were developed to solve the problem. SEDCs, TSRs and FSCs were put into practical operation in 2007.

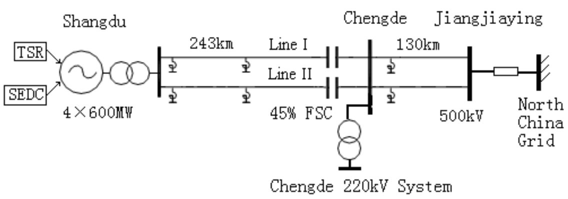

Figure 5: The one-line diagram of the Shangdu system.

5.2 Parameters of the Improved Models

1) The turbine-generator shaft

The torsional frequencies of the four generators are shown in Table 1. The typical coefficients of the mechanical damping model (3) were obtained with field-test data and listed in Table 2. To save place, other shaft model parameter won't be listed here.

Table 1: Modal Frequencies of the Shangdu T-Gs.

Gen.#	mode #1	mode #2	mode #3
1	15.33	26.12	30.54
2	15.32	26.12	30.52
3	15.22	26.04	30.51
4	15.19	26.01	30.25

Table 2: Coefficients of the mechanical damping model.

Mode #	α_m	β_m	c_m	k_m
1	0.010	25.2	0.005	0.135
2	0.007	31.0	0.006	0.135
3	0.005	20.0	0.012	0.180

2) The excitation system with SEDC

The standard IEEE ST4B AVR and IEEE PSS2B PSS models (Kamwa et al., 2005) are modified to represent the excitation system with SEDC included, of which the critical time constants are measured through filed tests, i.e., $T_d = 8.0$ ms, $T_r = 4.0$ ms .

3) MOV and the protective gap

MOV has three types of protection, as shown in Table 3. Once MOV protection is triggered, the gap is controlled to spark within 2 ms and then capacitors are bypassed for a time period (generally 3 seconds) or until the fault is completely cleared.

Table 3: The settings of MOV and the protective gap.

MOV protection	Settings	Actions
Over-current	12 kApeak	Gap spark and single-phase bypassed
Excess-energy bypass	22 MJ	Gap spark and single-phase bypassed
Excess-energy bypass without reclosing	26 MJ	Gap spark, 3-phase bypassed with the recloser locked

5.3 The Short-circuit Fault

On August 8, 2010, the system operated normally before the fault. At 20:16:58, a phase-to-ground fault happened on phase-A due to a lightning strike on Line II at 88km from Shangdu. The faulted line was tripped from Chengde and Shangdu sides after 55 and 63 milliseconds respectively. The recloser at Shangdu side reclosed successfully. However, the recloser at Chengde side failed and then phases B and C were tripped off about 89 milliseconds after the fault. Consequently, Line II was disconnected at

Chengde side. Divergent SSR appeared at Units #1 and #2. TSR then tripped Unit #1 about 3.546 seconds following the fault. Thus SSR converged rapidly. However, 6.388 seconds later, Unit #2 was tripped by its TSR because the accumulated fatigue loss-of-life exceeded its setting values. During the process, the shaft speed data were recorded.

5.4 Actual Measurements Vs. Simulations

A specific analysis on the above-mentioned fault was carried out with the improved SSR-EMS model. The simulation results are compared with actual measurements, as illustrated in Figures 6-9, in which the modal speeds of each generator as well as its corresponding upper envelope are plotted. It can be obviously observed that the actual measurements are basically in accordance with the simulated curves. Of course, there are some inconsistent "burs" on the upper envelopes for actual measurement due to noises in the obtained signals.

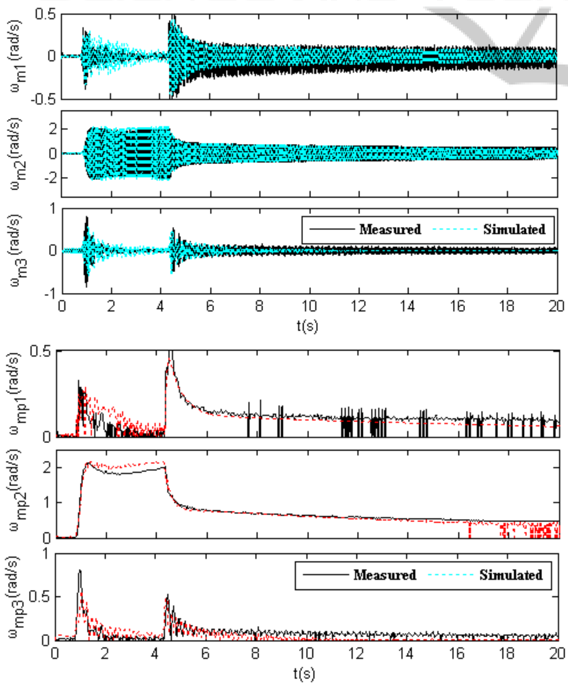

Figure 6: Measured vs. simulated SSR dynamics (unit #1).

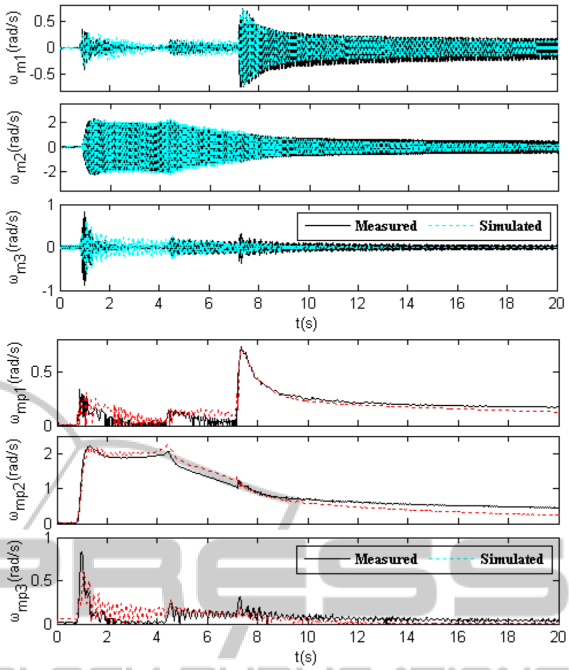

Figure 7: Measured vs. simulated SSR dynamics (unit #2).

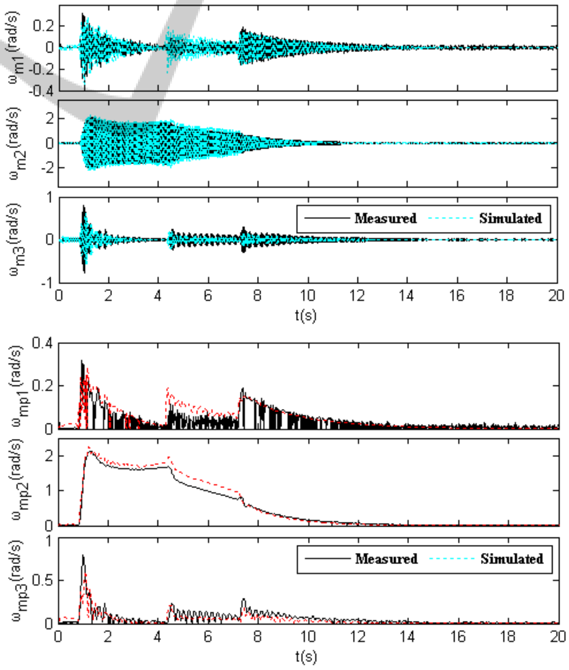

Figure 8: Measured vs. simulated SSR dynamics (unit #3).

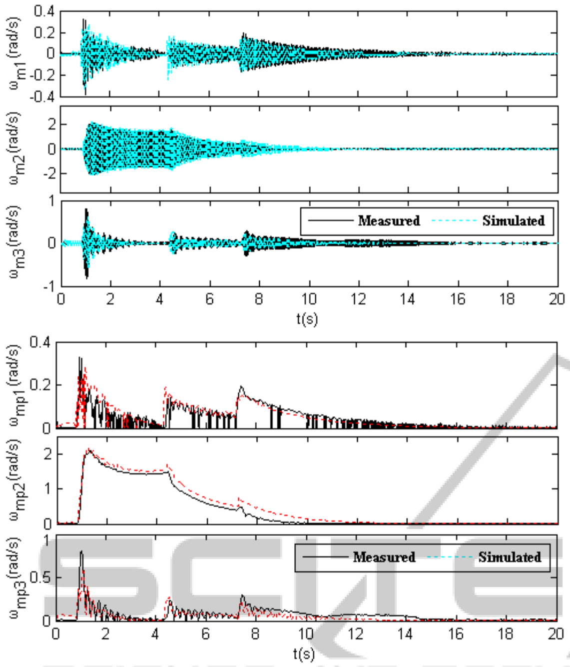

Figure 9: Measured vs. simulated SSR dynamics (unit #4).

6 CONCLUSIONS

Electromagnetic simulation is critical to SSR analysis and control-design. This paper presents several improvements in the modeling of SSR-EMS: i) the lumped mass-spring model with adjustable and nonlinear mechanical damping to simulate the variation of mechanical damping under different operating conditions and system disturbances; ii) a series compensation model incorporating MOV and the gap protection logic for accurate modeling of practical FSC when confronted with serious faults; iii) an EMS model of SEDC to reflect the dynamics of the power-electronic exciter. To verify the effectiveness, the improved model is used to analyze a short-circuit fault that occurred in a real system, i.e., the Shangdu series-compensated power system. The simulation results are compared with the field measurements and a good consistency is discovered.

ACKNOWLEDGEMENTS

This work is supported by National Natural Science Foundation of China (51077080 and 51037002) and State Key Lab. of Power System (SKLD11M02).

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