Test Results of Three Excitation Systems for Generators Suffering Continuous Voltage Flicker Disturbance

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Abstract-- This paper uses field test methods to compare the dynamic stability of three types of excitation systems, static excitation systems, brushless rotating excitation systems, and digital excitation control system, at the Tong-Shiao Generation Station of the Taiwan Power System. Three electric arc furnaces in this area produce continuous disturbance of voltage flicker (voltage fluctuation). The dynamic performances of generators and effects of voltage flicker will be evaluated by a series of field tests and measurements. At first, the field measurement is taken by injecting a small step signal into the reference input of the excitation systems for the generators at no-load. The system responses are examined and compared with the IEEE standard 421.2 recommendation to check the stability conditions. The tests for the generators at on-load are repeated again. Then the outputs of the generators are continuously monitored during the operation of the electric arc furnaces. The dynamic characteristics of the generators with different excitation systems are compared to reveal the effect of voltage flicker.

Index Terms---static excitation system, voltage flicker, dynamic stability, digital excitation control system, brushless rotating excitation system;

I. INTRODUCTION

An electric arc furnace (EAF) feeder is connected to the 69kV bus in the substation of the Tong-Shiao Generation Station of Taiwan Power System. The EAFs are operated during the off-peak load period when the system short circuit impedance is low. This introduces serious voltage flicker (voltage fluctuation) and influences operation of generators. Three types of excitation systems, static excitation system (SES), brushless rotating excitation system (BRES), and digital excitation control system (DECS), are adopted at this station. Particularly, the DECS was the first one used in the Taiwan Power System in June 1998. According to the IEEE Committee report [1], the DECS mainly uses the software control. It will be mainstream of excitation systems in the future, with easy adjustment, self diagnostic capability, more flexibility, better reliability, enhancing interfacing ability, and good stability. The Ontario Hydro of Canada has shared worthy experiences in applying DECS since 1988 [2]. For an aging generator with an old excitation system, the retrofit may be easy due to replacement with DECS [3]. It is planned to replace the old excitation systems of some generators by DECSs in the Tong-Shiao Generator Station. However, the effects of voltage flicker disturbances should be evaluated carefully. It is required that the generators have enough stability.

Many reports have focused on the effect of excitation control systems on generator behaviors. With proper designing the parameters of excitation systems, a fast exciter can be an effective means of enhancing machine stability. An analysis develops insights into effects of excitation systems for providing damping of machine oscillation [4]. Suitable excitation system models used in power system stability studies are presented [5,6]. Excitation control systems play an important role in the transient and oscillatory stability of generation units [7].

This paper uses field test methods for generators under no-load and on-load to assess the dynamic stability of three types of excitation systems at the Tong-Shiao Generation Station. The system responses are examined and compared with the IEEE standard 421.2 [8] recommendation to check the stability conditions. Additionally, it compares the dynamic characteristics of generators with different excitation systems suffering from continuous disturbance of voltage flicker. The results of this study will provide a valuable reference for future operating, tuning and adopting of excitation systems at the Tong-Shiao Generation Station.

II. SYSTEM DESCRIPTION

The Tong-Shiao Generation Station has five combined cycle generation units with total capacity of 1416MVA. This represents about 5.5% of the Taiwan power generation capacity. The one line diagram of this station is shown in Fig. 1. Two 161/69 kV 200 MVA transformers are installed to supply three EAF factories and other local loads. Gas turbine (GT) generators of units 1 and 2 are equipped with SESs. The SES structure is shown in Fig. 2. The equivalent model of the SES can be represented by the IEEE-ST3A model. The power source of the half bridge rectifier of SES is supplied by a unit transformer. The automatic voltage regulator (AVR) consists of a gain term and a lead-lag transient gain reduction (TGR) term to control the output voltage of the generator. The inner loop regulator controls the firing angle of SCRs. The manual/automatic gate can be selected by switching between manual or automatic excitation mode. Switching to manual mode, the field voltage keeps constant. Switching to automatic mode, the AVR can keep the terminal voltage of the generator. Since all generators are connected through transformers, the reactive current compensators are not used.

Recently, due to rapid developments of electronic devices and digital technologies, there is a growing trend toward the use of digital excitation control systems for synchronous generators. The DECS is not simply a digital version of the traditional analog counterparts, but contains sophisticated control functions which are not readily

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Fig. 1. The one-line diagram of Tong-Shiao Generation Station.

Fig. 2. The SES block diagram and field test points.

Fig. 3. The DECS block diagram and field test points.

Fig. 4. The BRES block diagram and field test points.

available in analog excitation control systems. They have the added advantage of being more flexible and reliable, allowing easy implementation of more complex control strategies, and interfacing with supervisory systems. Both steam turbine (ST) generators of units 1 and 2 are equipped with DECSs. The DECS structure is shown in Fig. 3. The control cores are implemented by digital technologies with one or more embedded microprocessors. The A/D and D/A converters are used to convert the signals between analog and digital forms. This system has high reliability due to the use of two independent controllers. When the main controller fails, the protection module recognizes the failure and switches over to the backup controller. The equivalent model of the DECS in this plant can be represented by the IEEE-ST4B model. The AVR is a proportional-integral (PI) controller. The proportional and integral gains affect the rise and settling time of system responses after a step change, respectively.

The brushless rotating excitation systems are employed in units 3-5. The BRES structure is shown in Fig. 4. No need for slip rings is the main feature since the AC exciter, diode rectifiers, and field windings of the generator are rotating with a shaft. The excitation voltage of the AC exciter is controlled by the SCRs which are powered from a unit power potential transformer (PPT). Then the output of the AC exciter is fed to the field windings of synchronous generator through the diode rectifiers. The equivalent model of the BRES can be represented by the IEEE-AC5A model.

III. DYNAMIC STABILITY TEST METHOD

The small signal method with time domain responses is a good method to test the dynamic stability of the excitation systems and the generators at no-load and on-load [8,9]. A no-load generator operates at synchronous speed and rating voltage but is not connected to the power system. A small step input signal is injected into the excitation system for the generator at no-load and on-load. This is intended to cause about 0.25%-2% change of terminal voltage. Subsequently, the dynamic performance is examined by the voltage responses of the generator. The dynamic response of a system subjected to a step input signal is shown in Fig. 5. The associated performance indices are rise time, overshoot, and settling time. The other index, damping ratio ζ , can be

calculated from the overshoot:

$$\text{Overshoot} = e^{-\zeta\pi/\sqrt{1-\zeta^2}} \quad (1)$$

The results of the dynamic test could be compared with the recommendation values in the IEEE Standard 421.2 [8] to verify the stability conditions.

Fig. 5. Dynamic stability response of a system subjected to a step input signal.

The field test procedures are as follows:

- (1) Determine the magnitudes of the input step signals. The test signals should not cause the tripping of the generator. The manuals of the SES and DECS indicate that to produce 2% change of terminal voltage needs 1 V dc and 400 counts signal, respectively [10,11]. The BRES needs -0.14 V dc to cause 2% change of terminal voltage.
- (2) Select measurement points. The measurement points of terminal voltage response are the PTs' secondary windings.
- (3) Measurement of data. A digital data recorder is used to obtain the response waveforms. Nevertheless the DECS can record the test trends by built-in recorder function.

IV. DYNAMIC TEST RESULTS

At first, the dynamic stability of three generators ST1(with DECS), GT1-1(with SES), and GT4-1(with BRES) at no-load are examined. At field tests, the injection of a small step signal into the reference voltage terminal of the

excitation system for the generator at no-load is to cause about 2% change of generator terminal voltage. The results of voltage responses are shown in Fig. 6 and the stability indices are shown in Table 1. All values satisfy the IEEE standard 421.2 recommendation. The voltage response of generator GT1-1(with SES) is the fastest and the GT4-1(with BRES) is the slowest. It is understandable that the response of GT4-1 is slower because the BRES structure has two d-axis transient time constants (T'_{do}), one of the AC exciter and the other of the synchronous generator.

Secondly, 1% step signals are injected to the excitation systems for the generators at on-load. The unit 1 works at one steam turbine(ST) generator with two gas turbine(GT) generators. The voltage response indices are presented in Table 2 and they are slower than those at no-load. The steady state reactive power changes are shown in Table 3. The generator ST1(with DECS) provides the largest percentage of reactive power compensation, and the GT1-1(with SES) gives the lowest percentage. The field test reveals that the dynamic performances of three generators at current settings are acceptable.

(a) generator ST1(with DECS)

(b) generator GT1-1(with SES)

(c) generator GT4-1(with BRES)

Fig. 6. The voltage step responses of no-load generators.

Table 1. The performance indices of generators ST1, GT1-1 and GT4-1 at no-load test

generator	rise time (sec.)	overshoot (%)	damping ratio	settling time (sec.)
ST1 (with DECS)	0.23	11	0.6	2
GT1-1 (with SES)	0.15	52.8	0.2	1.49
GT4-1 (with BRES)	0.5	0	0.8	0.6
IEEE-421.2 standard	0.1~2.5	0~80	0~1	0.2~10

Table 2. The performance indices of generators ST1, GT1-1 and GT4-1 at on-load test

generator	rise time (sec.)	overshoot (%)	damping ratio	settling time (sec.)
ST1 (with DECS)	1.13	23.3	0.42	4.5
GT1-1 (with SES)	0.51	10.9	0.58	4.2
GT4-1 (with BRES)	2.29	0	0.9	4.6

Table 3. The reactive power responses of generators ST1, GT1-1 and GT4-1 at on-load test

generator	generator rating (MVA)	generator operating condition			reactive power change	
		P (MW)	Q (Mvar)	PF	ΔQ (Mvar)	ΔQ (%)
ST1 (with DECS)	137.2	51	10	0.981	11	8
GT1-1 (with SES)	115.75	57	7	0.993	6	5.2
GT4-1 (with BRES)	119.2	68	10	0.99	8.3	7

V. EFFECT OF VOLTAGE FLICKER

The responses of generators suffering continuous disturbances of voltage flicker are assessed. The unit 1 works at one steam turbine(ST) generator with three gas turbine(GT) generators. The measurement is taken when the EAFs start a melting stage. The measurement results of the 161kV bus voltage and the 69kV EAF feeder voltage, reactive power, and active power are shown in Fig.7. The simultaneous measurement results of generator ST1(with DECS), GT1-1(with SES), and GT4-1(with BRES) are shown in Fig. 8-10, respectively. The results reveal that all generators have good stability and can successfully sustain the voltage flicker. In Fig.7, the EAFs start at the 20th second and they cause obvious larger voltage flicker. It is marked at the 27th second where the instantaneous changes of EAFs reactive power and active power are 39Mvar and 36MW, respectively. It causes the voltages of 69kV feeder and

161kV bus to reduce 2% and 1%, respectively. Then the corresponding responses of three generators are marked at the same time in Fig.8-10 individually and listed in Table 4. The difference in changes of generator terminal voltages is small because they are affected by the voltage of 161kV bus mainly. The generator ST1(with DECS) provides the largest percentage of reactive power compensation, and the GT1-1(with SES) gives the lowest percentage. The active power fluctuations have no particular relations.

Fig. 7. Measurement results of 161kV bus voltage and 69kV EAF feeder voltage and powers when EAFs start up.

VI. CONCLUSION

The method by injecting a small step signal into the excitation system is a good approach to assess the dynamic stability condition of generators. This technique allows a thorough study and provides a basis for comparison. The field test reveals that the voltage response of a generator with BRES is slower due to the essential limitation on its structure which has two direct-axis transient time constants.

The expected response of the generator with a SES or a DECS could be adjusted by changing the AVR settings easily. Particularly, the DECS mainly uses the software control so that it may be adjusted more accurately and flexibly. The current settings of three types of excitation systems at the Tong-Shiao Generation Station satisfy the IEEE standard 421.2 recommendation and the stability is enough to stand the voltage flicker (voltage fluctuation) disturbances caused by nearby EAFs. The results of field tests will provide a valuable reference for future operating, tuning and adopting.

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Fig. 8. Measurement results of generator ST1(with DECS) when EAFs start up.

Table 4. Effect of voltage flicker on generators ST1, GT1-1 and GT4-1

generator	generator rating (MVA)	generator operating condition			terminal voltage change ΔV (%)	reactive power change		active power change	
		P (MW)	Q (Mvar)	PF		ΔQ (Mvar)	ΔQ (%)	ΔP (Mvar)	ΔP (%)
ST1 (with DECS)	137.2	85	13	0.99	-0.77	4.7	3.4	3.8	2.8
GT1-1 (with SES)	115.75	58	8	0.99	-0.77	1.6	1.4	1.2	1
GT4-1 (with BRES)	119.2	71	14.5	0.98	-0.71	3	2.5	-4.8	-4

Fig. 9. Measurement results of generator GT1-1(with SES) when EAFs start up.

Fig. 10. Measurement results of generator GT4-1(with BRES) when EAFs start up.

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