Emergency Generator Startup Study of a Hydro Turbine Unit for a Nuclear Generation Facility

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***Abstract*—This paper reports the implementation of synchronous generator, induction machine, hydro turbine, and governor system, and excitation and automatic voltage regulator system models for transient stability study. These models are frequency dependent and are suitable for system transient studies involving drastic frequency changes, including generator startup and emergency load startup. A computer simulation program has been developed using these models for a transient stability study. The developed program is further validated and verified using real system testing data that includes the cases of generator startup and full-load shed in a nuclear power generation plant. Validation results show overall an excellent correlation between the computer simulation and the field-testing data. As a result, the program has been accepted by the plant for system modeling and emergency generator startup simulation studies.**

***Index Terms*—Frequency-dependent synchronous machine, generator startup, hydro power generation, induction machine and network models, start emergency load, transient stability study.**

I. INTRODUCTION

UNDER certain situations, frequency in a power system may drastically vary from its nominal value. One example of these situations is the generator startup. In such a case, a synchronous generator is started from a cold standby condition with both the initial frequency and the voltage set at zero. Another example in this category is the prolonged or sustained subsynchronous oscillation in a large power system consisting of multiple synchronous generators. Under this condition, frequency across the system is distributed corresponding to the locations of different coherent synchronous generator groups in an uneven fashion. Due to the lack of frequency dependent machines and system models, most commercially available computer simulation programs, for power system transient stability studies, fail to produce reliable or even meaningful analytical results when applied to the aforementioned situations.

To correctly model frequency and voltage characteristics of power system components, a special transient stability analysis program has been developed to handle the conditions in which the system undergoes considerable frequency variations during the transient. This program includes: 1) implementation of IEEE-type synchronous generators with damping windings on both direct and quadratic axes, consideration of the saturation effect to generator parameters and the ability to count for frequency variation ranges from zero to a significant overshoot; 2) implementation of frequency dependent induction machines with different makes and configurations; and 3) implementation of a power system's frequency dependent network model. These models are suitable for power system transient stability studies in cases with and without significant frequency changes.

The newly developed program is validated and verified by field-testing measurements from a real system. System configuration and operating conditions are recreated including manual and relay controlled switching actions and other time events. Synchronous generator, induction motor, bus real power and reactive power loadings, and some other key system dynamic responses are plotted and compared to the actual field measurements to assess the validity of the models. An excellent correlation is found between the simulation results and those from the field measurements. As a conclusion, the developed transient stability analysis program is accepted by a nuclear generation plant for emergency generator startup studies. The program can be used to simulate any power system transients with or without drastic frequency variation while producing reliable and satisfactory results.

II. TESTING SYSTEM DESCRIPTION

The test system is a nuclear generation plant and its emergency power backup. A simplified system one-line diagram is shown in Fig. 1.

Loads connected to 4-kV buses and the subsystems down below are normally powered up by the grid through two 4-kV buses, 4 kV1 and 4 kV2. These loads represent the emergency load in the nuclear generation plant.

Generator KGEN2 located in the nearby hydro generation station is in a cold standby condition and two circuit breakers, 1 T-7 and 2 T-7, are normally open. When there is power loss from the grid, an emergency startup signal is received at KGEN 2 starting it immediately and two 4 kV standby buses, 1 T and 4 kV 2 T, are then energized. By setting the voltage relay connected to the generator 13.2 kV terminal bus, 1 T-7 and 2 T-7 will be closed at the appropriate time to energize the emergency loads in the plant.

Generator KGEN 2 is a hydro unit. A schematic drawing of the studied system is shown in Fig. 2.

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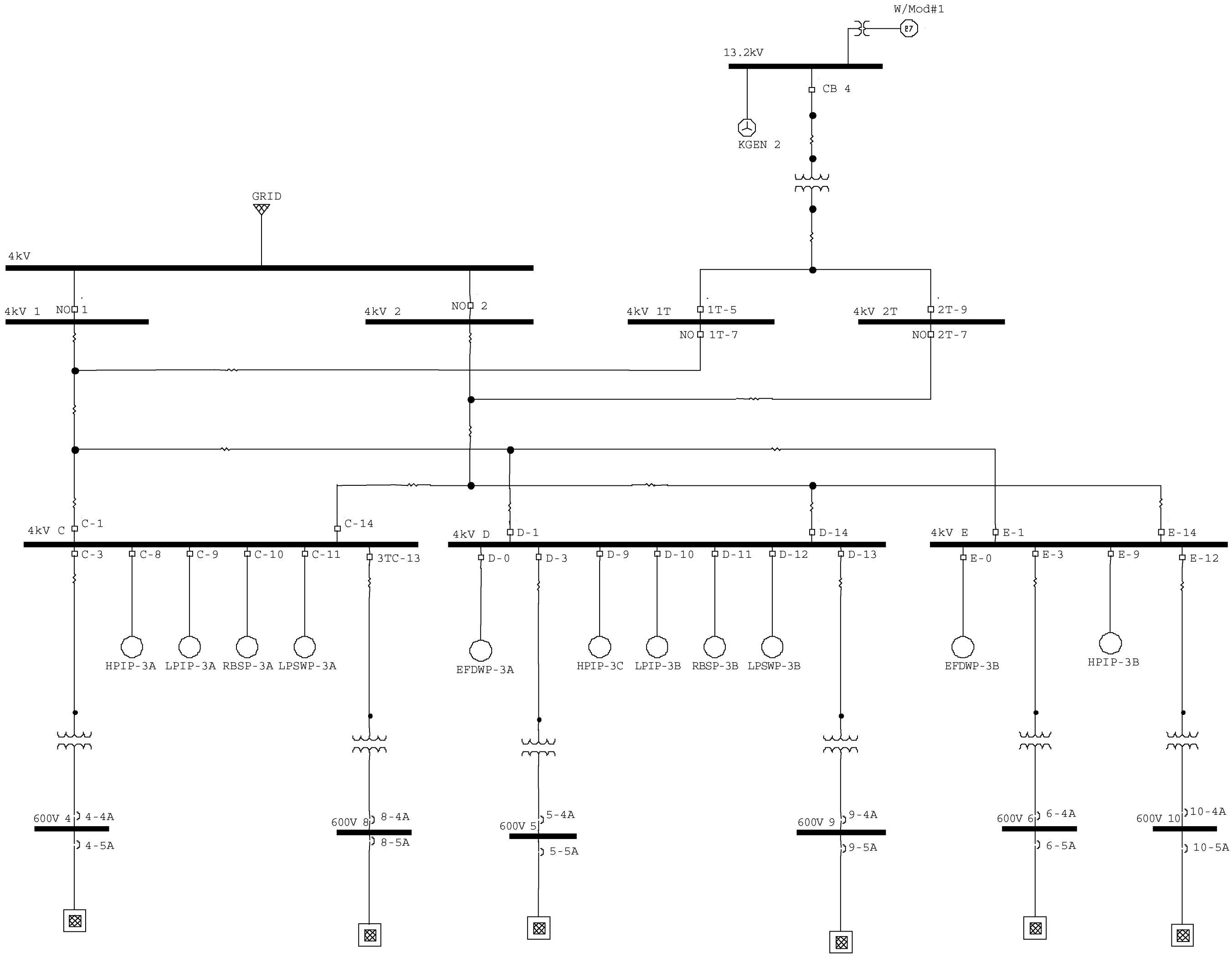


Fig. 1. Simplified system one-line diagram.

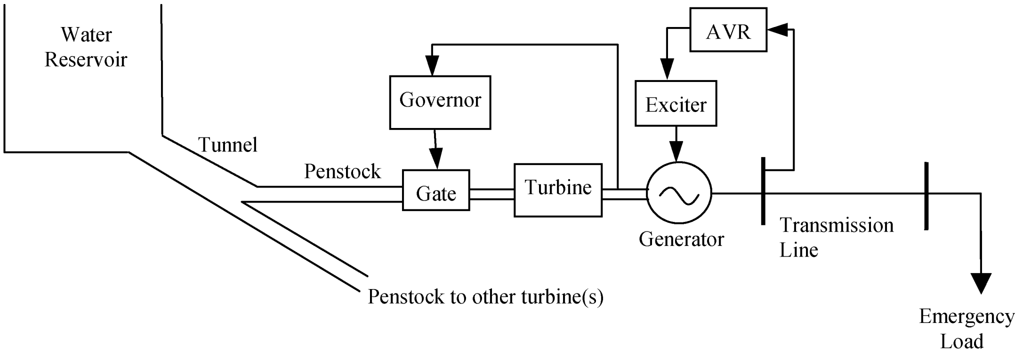
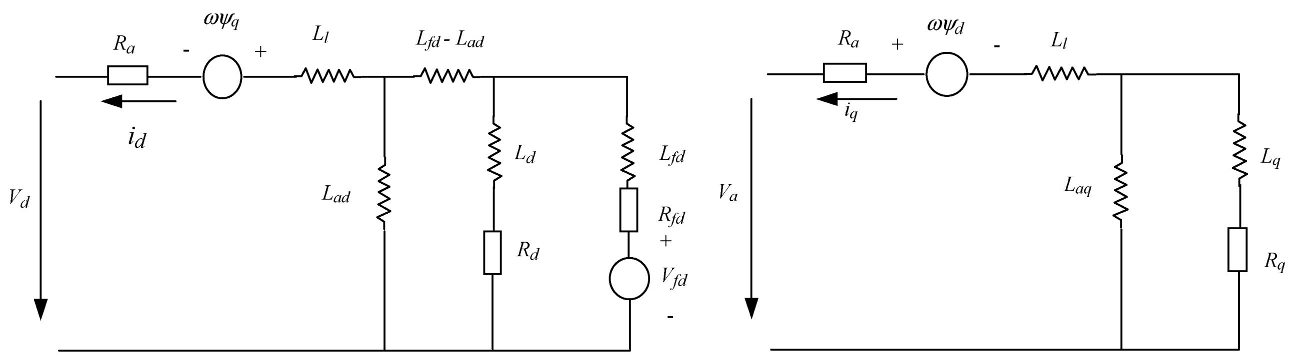


Fig. 2. Schematic drawing of the hydro generation station and its load.

This system includes a synchronous generator, a hydro turbine with a water tunnel, penstock and speed control governor, an excitation system with automatic voltage regulator (AVR), transmission line(s), and emergency loads. Emergency loads consist of both induction motors and some static load. Dynamic models have been developed to simulate each of these components for use in the transient stability study. Due to the fact that the system frequency during the generator startup process varies within a range from 0 to as high as 120%–130% of the nominal value, all the models must have the capability to account for this frequency variation. A brief description, of the frequency-dependent models of these aforementioned components, is given in the next section.



a) (b)

Fig. 3. Synchronous generator equivalent circuit model. (a) Generator direct-axis equivalent circuit. (b) Generator quadratic-axis equivalent circuit.

III. SYNCHRONOUS GENERATOR, TURBINE, EXCITER, ASSOCIATED CONTROL SYSTEMS, AND INDUCTION MACHINE MODELING

This section describes the synchronous machine, the hydro turbine and governor system, the excitation and AVR system, and the induction machine models used in the generator startup study. All the models are frequency dependent.

A. Synchronous Generator Modeling

Based on the manufacturer data sheet, the IEEE 2.1 synchronous generator model is used. This model is given and described in [4]. An equivalent circuit diagram of the model is shown in Fig. 3.

This model does not include the frequency in its model parameters and thus allows independent consideration of changes in frequency. Generator saturation characteristics are also accommodated by adjusting model parameters.

B. Turbine and Governor System Modeling

The turbine/governor system includes water dynamics in the water tunnel, penstock, hydro turbine, and speed governor control. As shown in Fig. 2, when the generator is started, water from the reservoir is released flowing through a single head gate into a common power tunnel, splitting into multiple flows. Each passes a wicket gate, then a penstock, and finally enters the turbine runner of the generator unit, providing mechanical power to the generator. The wicket gate is controlled by a mechanical–hydraulic governor, which opens and closes the gate according to the preprogrammed control functions as described in [7]. The schematic diagram of the power tunnel, penstock, wicket gate, and governor control system is illustrated in Fig. 4.

C. Excitation and AVR System Modeling

The excitation system of the generator is a static type and is equipped with an AVR. The transfer function block diagram of this excitation and AVR system is shown in Fig. 5.

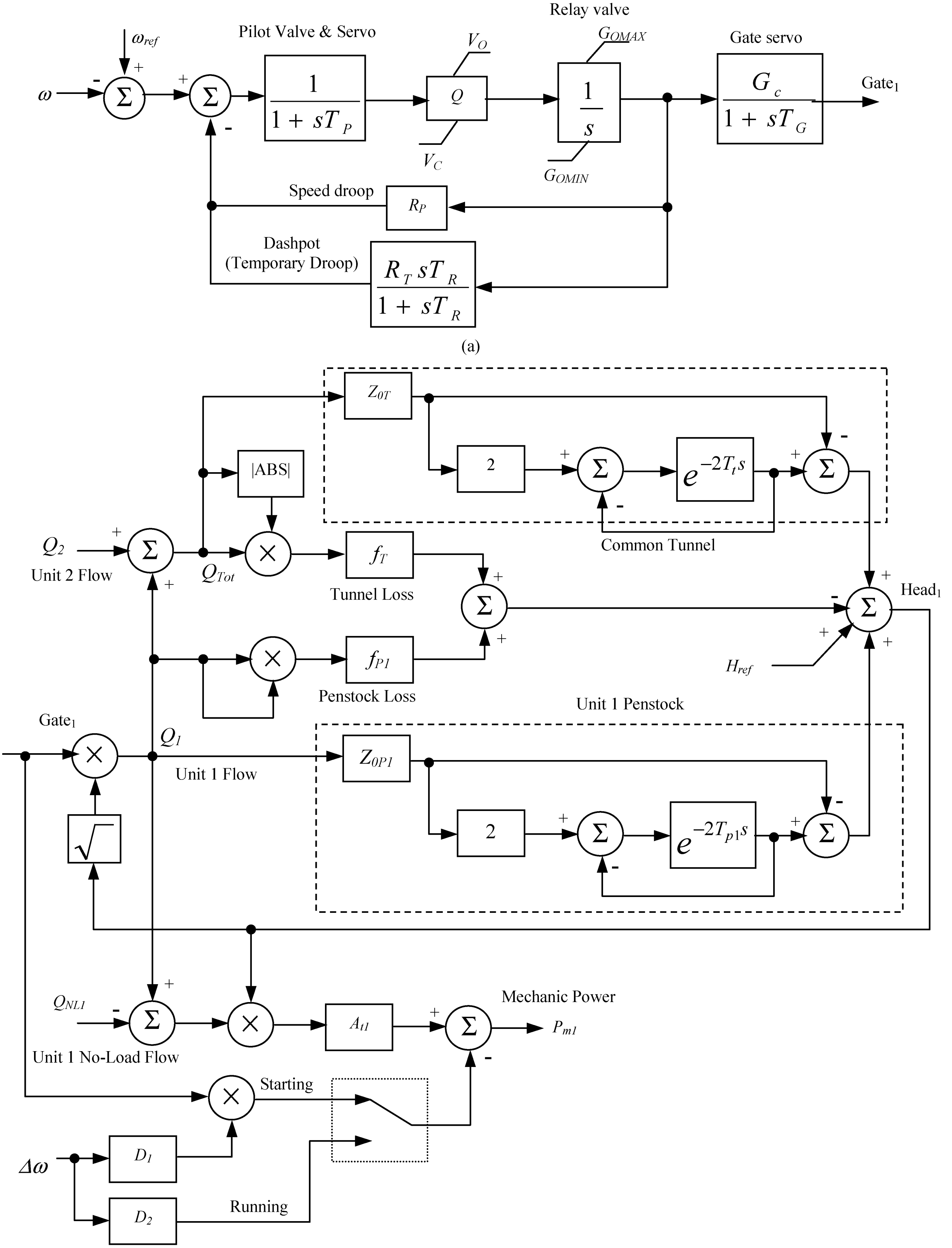
This excitation and AVR system includes five main functional blocks:

1) main loop consisting of a Rectifier and an Amplifier, which, according to the voltage error signal, generates a corrective excitation voltage and applies it to the field winding;
2) dc flashing circuit that is used to supply excitation voltage to the field winding when the generator is initially started; a V/Hz (voltage per Hz) control circuit will switch this from manual mode to automatic mode (connecting the field winding directly to the excitation and AVR system) based on a presetting (usually 0.7–0.8 per unit); the field flashing circuit is modeled by an *RL* circuit with a dc source given in [7];
3) V/Hz limit and protection unit which reads both the generator terminal voltage and the frequency to calculate the generator V/Hz value and, if it is too high, sends a signal to a low value selector that tends to reduce the excitation voltage to the field winding;
4) load compensator that senses both the generator terminal voltage and current to regulate the generator output voltage to compensate for load changes;
5) stabilizing feedback loop, which based on the generator field winding current, to produce the necessary stabilizing signal added to the exciter.

D. Induction Machine Modeling

The emergency loads are started at approximately 70%–90% of the system rated frequency output. At this time, all induction motors among the emergency loads are to be accelerated, or in another words, those motors are started in an under-frequency condition. In addition, during the motor acceleration, an over-frequency condition can occur due to the generator's response. Thus, appropriate induction motor model must be employed to study the motor starting transient for both under and over frequency conditions. An equivalent circuit model for a double-cage induction machine is illustrated in Fig. 6. The model parameters used in this study are based on the estimated results given in [7]. Essentially, in this model, the parameters are independent of the system frequency. This concept can be used to develop other types of induction machine frequency dependent models. These machine models should be used in the studies where the system frequency has large variation in the magnitude such as the generator startup, large load shed, or addition.

Due to the existence of the over frequency condition, machine load models need to extend to cover the over-speed characteristics, which are also correctly modeled in the program.



(a)

(b)

Fig. 4. Hydro turbine and governor system model diagram. (a) Speed governor and gate control system. (b) Hydro turbine and water tunnel system.

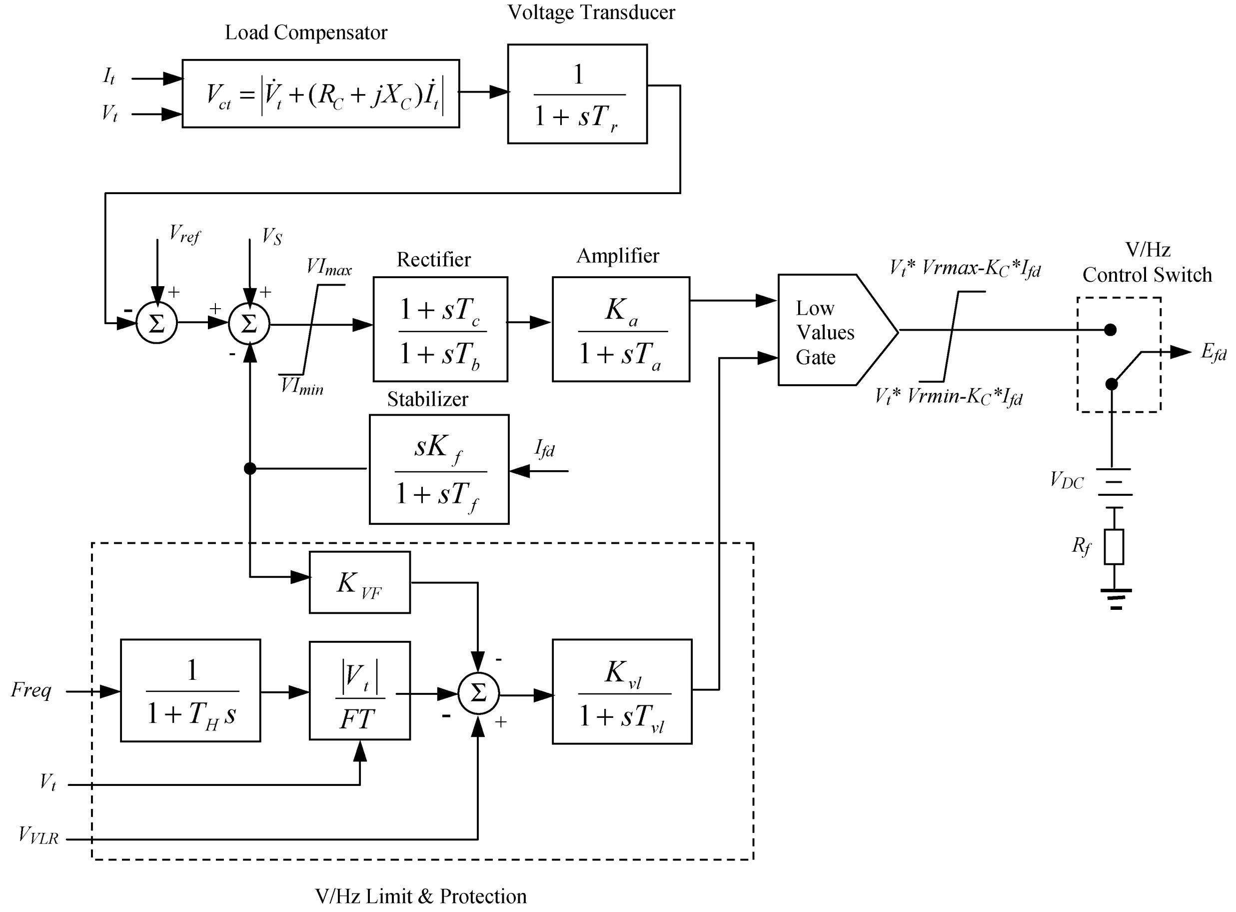


Fig. 5. Transfer function block diagram of the excitation and AVR system.

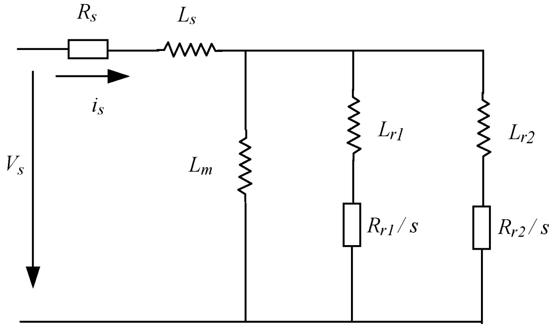


Fig. 6. Frequency-dependent equivalent circuit model for double-cage induction machine.

IV. MODEL VALIDATION AND VERIFICATIONS

Models described in the above section are all validated and verified by comparing the simulation results of the program with the actual field measurements. Two field tests are selected. System configurations and testing conditions of these two tests are described in this section, with the comparison of the program simulation results and the field measurements.

A. Generator Startup Test

This test is an actual generator startup for the system described in Fig. 1. In this test, hydro unit KGEN2 is started at time reference 0 second by opening the water gate and applying dc flashing voltage to the generator field winding. Water flows through the power tunnel, the penstock, and the gate, driving the turbine to rotate the generator. At the same time, the battery powered dc supply flashes the generator field winding, inducing the initial rotor flux inside the generator air gap and the stator windings, resulting in a voltage at the generator terminal. As both generator speed and terminal voltage gradually build up and reach to certain levels, the dc flashing voltage will be disconnected, transferring the excitation source to the exciter and AVR system named "automatic mode," Once the generator terminal voltage reaches the pre-specified value based on the generator rated output voltage, the voltage relay mounted on the generator terminal bus 13.2 kV closes the circuit breakers 1 T-7 and 2 T-7, thus connecting the emergency load to the generator.

Two test conditions are simulated.

- *Test A (T2)* The emergency loads are started at 76% of the generator rated output voltage.
- *Test B (T1)* The emergency loads are started at 94% of the generator rated output voltage.

Figs. 7–9 show generator frequency, voltage, and electrical power responses from Test A. An excellent correlation between the simulation and test results is clearly displayed in the figures, indicating that the synchronous generator model, the hydro turbine and governor model, and the excitation and AVR model in

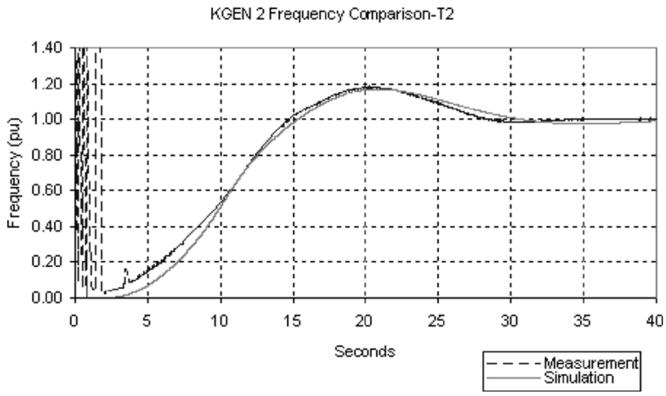


Fig. 7. Generator KGEN2 frequency (Test A).

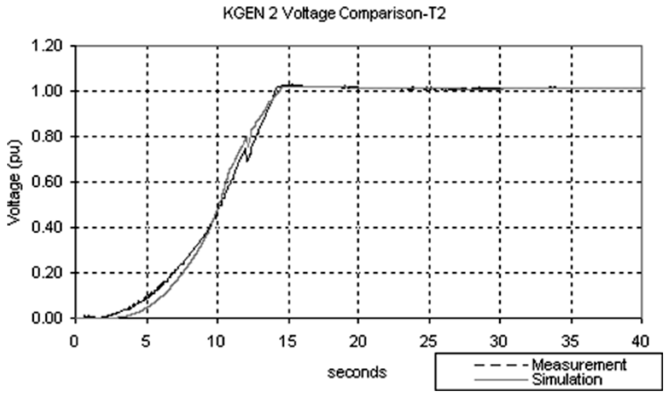


Fig. 8. Generator KGEN2 voltage (Test A).

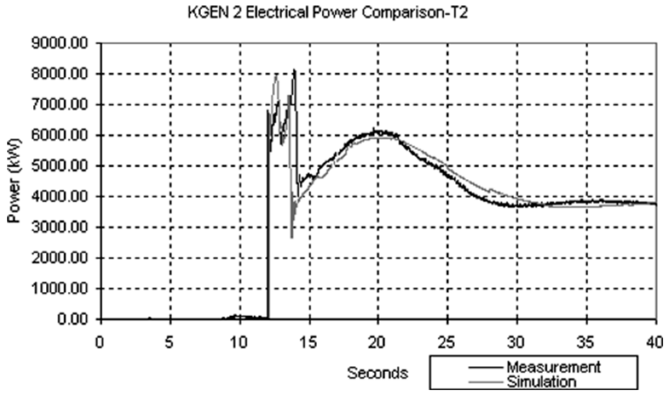


Fig. 9. Generator KGEN2 electrical power (Test A).

the program correctly capture the dynamic performance of these components.

Figs. 10–15 show induction motors, HPI-3B and MDEFW-3B, emergency start responses, including motor terminal voltage, current, and electrical power. An excellent correlation is also found between the simulation results and those from the field measurements.

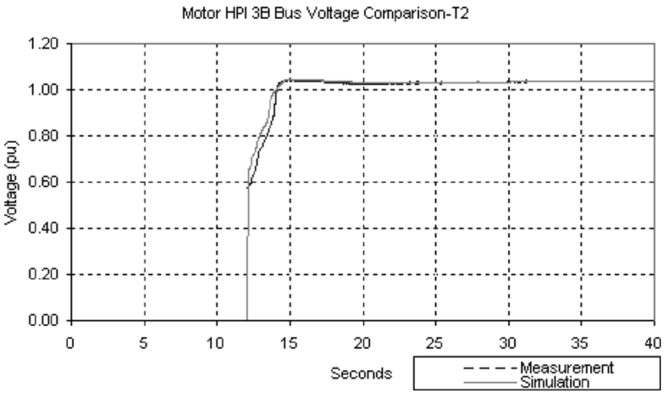


Fig. 10. Motor HPI-3B voltage (Test A).

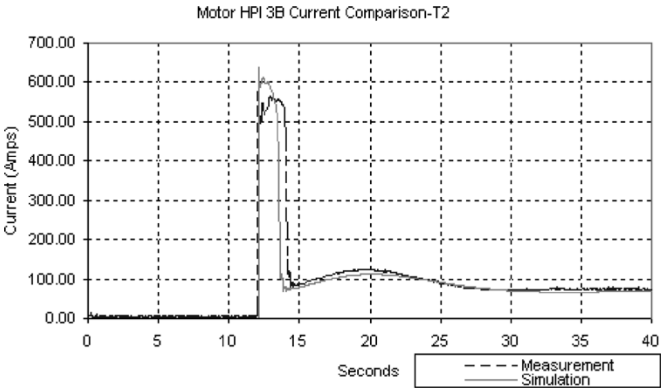


Fig. 11. Motor HPI-3B current (Test A).

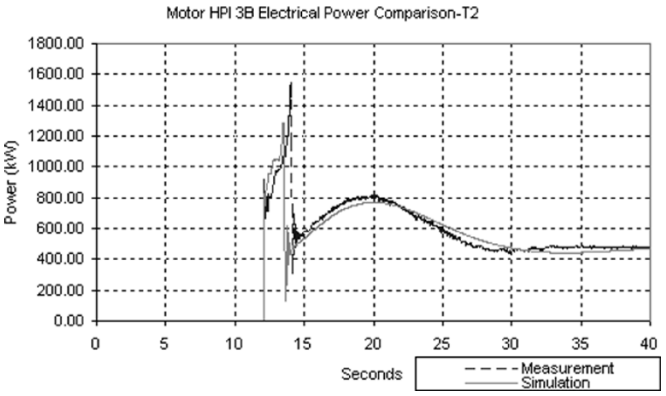


Fig. 12. Motor HPI-3B electrical power (Test A).

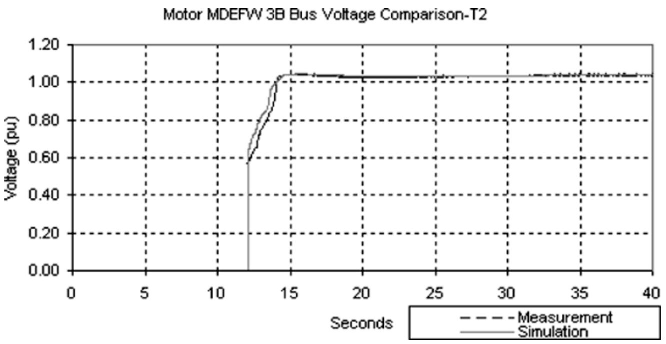


Fig. 13. Motor MDEFW-3B voltage (Test A).

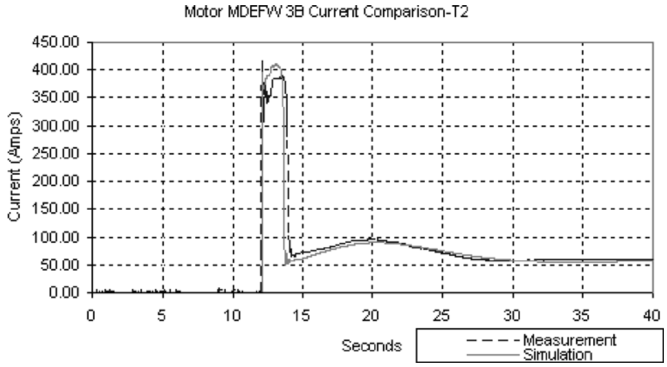


Fig. 14. Motor MDEFW-3B current (Test A).

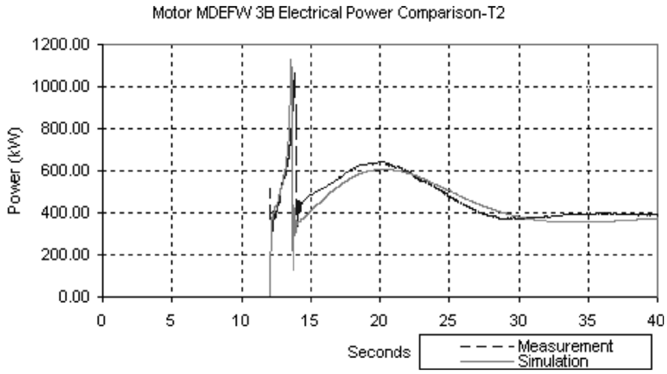


Fig. 15. Motor MDEFW-3B electrical power (Test A).

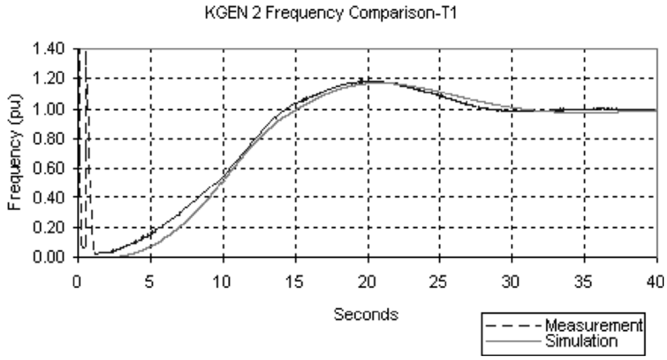


Fig. 16. Generator KGEN2 frequency (Test B).

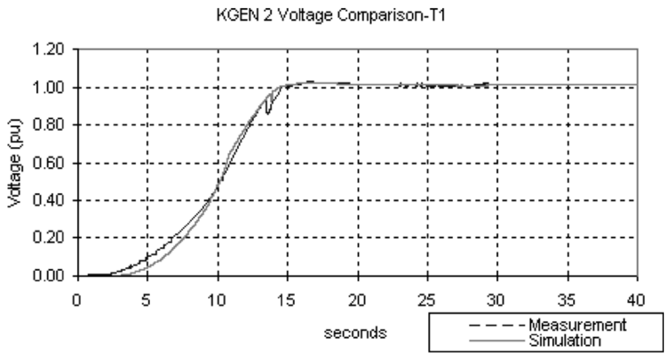


Fig. 17. Generator KGEN2 voltage (Test B).

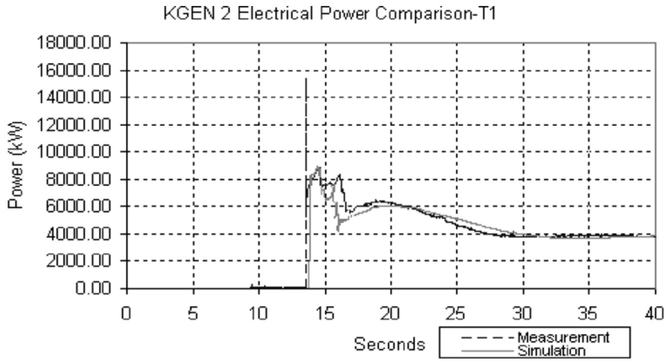


Fig. 18. Generator KGEN2 electrical power (Test B).

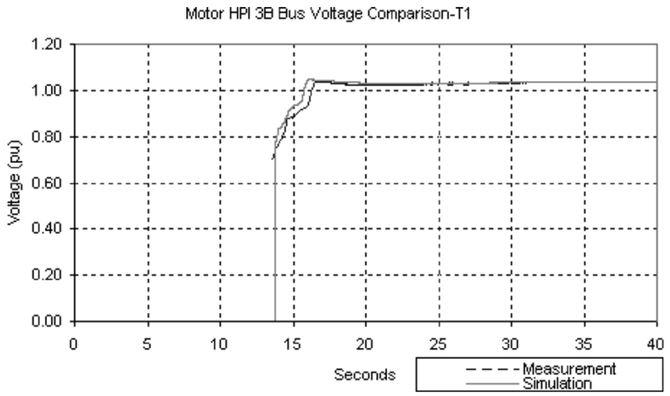


Fig. 19. Motor HPI-3B voltage (Test B).

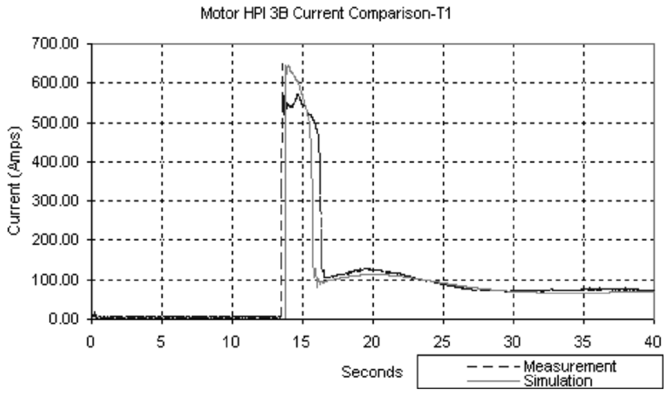


Fig. 20. Motor HPI-3B current (Test B).

Figs. 16–24 show generator and emergency starting motor responses for Test B. Excellent correlation is also observed between the simulation results and those from the field measurements.

B. Load-Shed Test

To further check validity of the program, a load-rejection test is conducted. The testing system for the load-rejection study consists of KGEN 2 generator and its associated controls, a transmission cable, and an equivalent initial load of 70 MW and 16 Mvar as shown in Fig. 25.

The system is initially operating at steady state. A full-load rejection takes place by opening circuit breaker CB2 at 2.12 s. Generator frequency and terminal voltage are plotted and compared with the field measuring data. Results are shown in

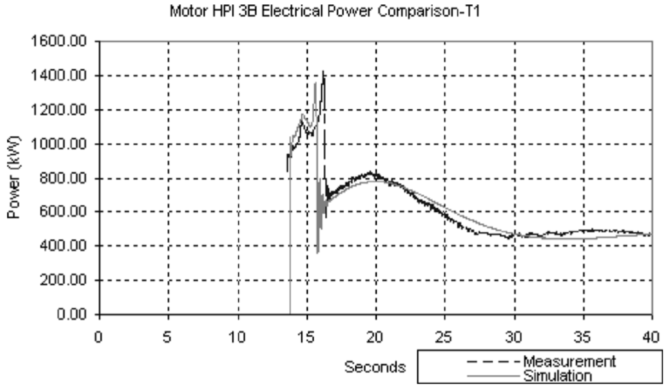


Fig. 21. Motor HPI-3B electrical power (Test B).

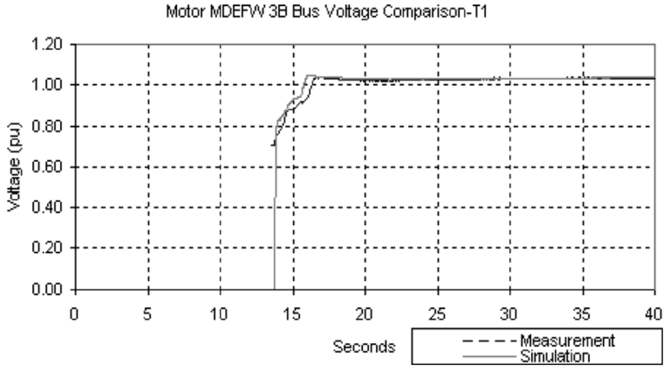


Fig. 22. Motor MDEFW-3B voltage (Test B).

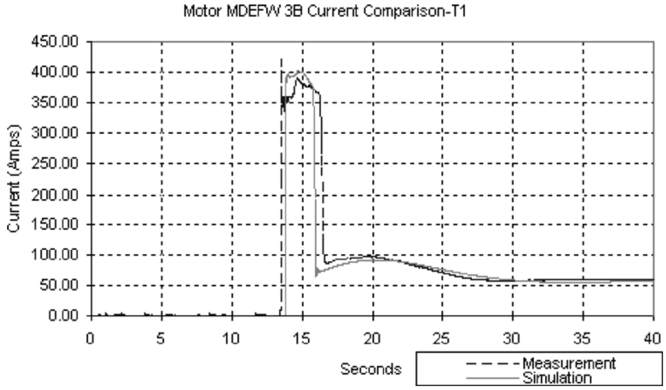


Fig. 23. Motor MDEFW-3B current (Test B).

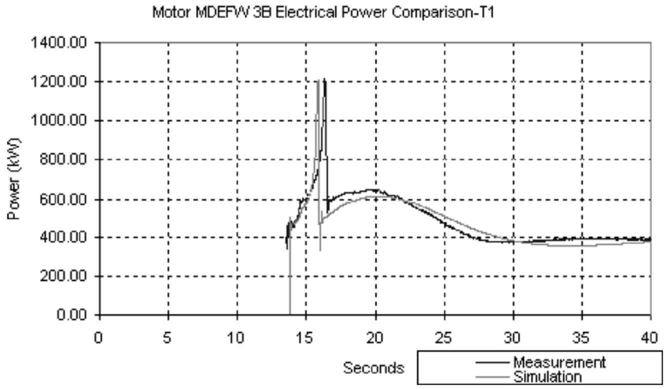


Fig. 24. Motor MDEFW-3B electrical power (Test B).

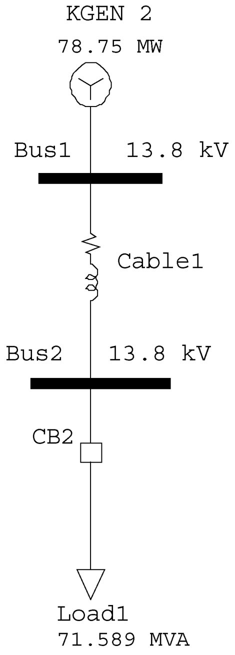


Fig. 25. Testing system configuration for load rejection study.

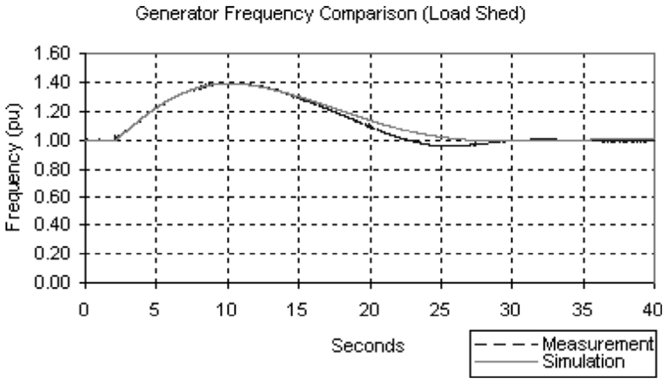


Fig. 26. Generator frequency response for load rejection.

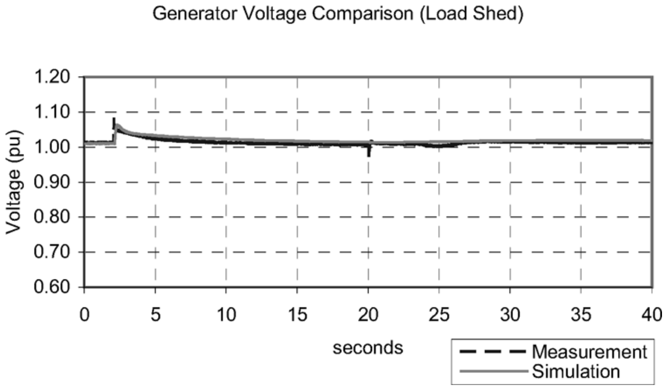


Fig. 27. Generator terminal voltage responses for load rejection.

Figs. 26 and 27. As can be seen from the plots, results show that both generator frequency and terminal voltage responses demonstrate excellent correlation between the simulation and field-testing data.

V. CONCLUSION

A special transient stability program with a frequency-dependent synchronous generator model and induction machine model, a turbine and governor system model, and excitation and AVR system models has been developed. The program is validated and verified using real system testing data in a nuclear power generation plant. The testing conditions include a generator and emergency load startup, as well as a full-load rejection. During these tests, system and generator frequency as well as generator terminal voltage undergoes a wide range from 0 to up to 120% of their nominal values. Comparisons between the simulation results from the developed program and the field measurements prove these models correctly reflect synchronous generator and induction machine frequency dependent dynamic characteristics; thus the program can be used reliably and effectively to provide analytical results for system transient assessment.

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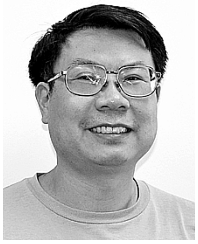

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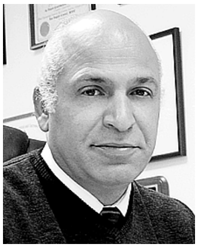

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