

A Diesel Generator Model with Fluctuating Engine Torque Including Magnetic Saturation for Transient Analysis using XTAP

Orie Sakamoto[†]

Abstract – Diesel engine generators are widely used in the world, especially in remote site power systems as distributed generators. A weak distribution feeder with a small diesel engine may suffer from voltage and power fluctuations due to misfiring of the engine cylinder. In this study, new generator model with example engine torque was developed for the electromagnetic transient analysis program for power systems named XTAP. The configuration and verification results of the developed model are presented in the paper. The model is considered to be useful for analyses of small power systems with those diesel engines.

Keywords: Diesel engine generator, Electromagnetic transient analysis, Power systems, Synchronous generator, XTAP

1. Introduction

Diesel engine generators are widely used in the world, especially in remote site power systems as distributed generators. A weak distribution feeder with a small diesel engine may suffer from voltage and power fluctuations due to misfiring of the engine cylinder. In order to investigate effects of these phenomena to electric power quality in conditions similar to actual power systems, electromagnetic transient (EMT) analysis is very useful.

An EMT analysis program for power systems named XTAP (eXpandable Transient Analysis Program) was developed by Central Research Institute of Electric Power Industry and is widely used in Japan. The two-stage diagonally implicit Runge-Kutta (2S-DIRK) method is adopted for numerical integration in XTAP [1]. Convergence performance was also improved [2] and initializations of whole simulated system are available [3], therefore, XTAP can improve numerical stability, convergence performance, and expandability of new models for transient analyses of power systems.

XTAP is considered to be useful to simulate those small power systems with existing problems. In this study, a new diesel generator model with fluctuating engine torque was developed using XTAP. The configuration and verification results of the model are described in this paper.

2. Developed Diesel Generator Model

2.1 Overall structure

The target of this study is small-scale synchronous diesel engine generators to supply local electric power systems.

[†] Corresponding Author: Dept. of Engineering and Applied Sciences, Sophia University, Japan. (orie-sakamoto@sophia.ac.jp)
Received: November 17, 2014; Accepted: December 26, 2014

The newly developed diesel generator model for XTAP is composed in the form of Voltage-Behind-Reactance (VBR) model.

The sub-transient inductances for d - and q -axis are assumed to be non-salient here for simplicity, because the purpose of this study is basic consideration of fluctuating mechanical torque of diesel generator, not of detailed modeling of synchronous generator.

The generator dynamics can be represented by the voltage source behind the sub-transient inductance L'' when sub-transient inductances have no saliency. The d - and q -axis magnetic flux which make the internal voltage behind L'' have only rotor magnetic flux component as described below.

In the developed model, the voltage source e'' is connected to the system through the sub-transient inductance L'' and the armature resistance R_a in abc phase domain. Since diesel generators are salient machine for transient time domain, single d -axis and single q -axis damper winding were into consideration. The magnetic saturation characteristics were also included in the model.

2.2 Equations for generator dynamics

The equations used in the developed model are given in this section. The variables for the armature circuit are calculated in SI values. For the other variables, per unit representations are used. The base values are the generator rated capacity, the rated terminal voltage, and the rated rotational speed.

Since the target of this study is generators with non-salient sub-transient inductances as mentioned above, we can introduce the sub-transient inductance L'' (p.u.H) as follows:

$$L_d'' = L_q'' = L'' , \quad (1)$$

where L''_d and L''_q are the d - and q -axis sub-transient inductance (p.u.H).

Stator voltage equations in abc phase are given by

$$\begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} = \begin{pmatrix} e''_a \\ e''_b \\ e''_c \end{pmatrix} - L''p \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} - R_a \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix}, \quad (2)$$

where R_a is the armature winding resistance (Ω); e_a , e_b , and e_c are the generator terminal voltage in abc phase (V); i_a , i_b , and i_c are the armature current of each phase (A). Symbol p denotes time derivative operator as shown in

$$pf(t) = df(t) / dt. \quad (3)$$

Variables e''_a , e''_b , and e''_c in (2) are the generator internal induced voltage behind L'' (V) and given by

$$\begin{pmatrix} e''_a \\ e''_b \\ e''_c \end{pmatrix} = C_{abc-dq0} \begin{pmatrix} e''_d \\ e''_q \\ e''_0 \end{pmatrix}. \quad (4)$$

Matrix $C_{abc-dq0}$ is the abc - $dq0$ transformation matrix; e''_d and e''_q are the generator internal induced voltage behind L''_d and L''_q (p.u.V). e''_d and e''_q are obtained from

$$e''_d = p\phi_{fkd} - \phi_{fkd}\omega_r, \quad (5)$$

$$e''_q = p\phi_{fkq} + \phi_{fkq}\omega_r, \quad (6)$$

where ω_r is the rotor angular velocity (p.u.rad/s).

Flux linkage ϕ_{fkd} and ϕ_{fkq} are the magnetic flux linkage behind L''_d and L''_q (p.u.Wb) and assumed here as

$$\phi_d = -L''_d i_d + \phi_{fkd}, \quad (7)$$

$$\phi_q = -L''_q i_q + \phi_{fkq}, \quad (8)$$

where i_d and i_q are the d - and q -axis armature current (p.u.A).

Per unit air-gap torque T_e (p.u.Nm) is expressed by

$$T_e = \phi_d i_q - \phi_q i_d. \quad (9)$$

The swing equations in per unit are given by

$$ps_g = \frac{1}{M} (T_m - T_e - Ds_g), \quad (10)$$

$$p\delta = \omega_0 s_g, \quad (11)$$

$$\omega_r = 1 + s_g, \quad (12)$$

$$\begin{pmatrix} \theta_a \\ \theta_b \\ \theta_c \end{pmatrix} = \begin{pmatrix} \theta_{a0} \\ \theta_{b0} \\ \theta_{c0} \end{pmatrix} + \omega_r t + \delta, \quad (13)$$

where s_g is the rotor angular velocity deviation (p.u.), T_m , the mechanical torque input (p.u.Nm), D , the damping coefficient (p.u.), δ , the rotor angle (rad), ω_0 , the synchronous rotor angular velocity (rad/s), θ , the phase angle (rad), and t , time (s).

2.3 Magnetic saturation characteristics

The magnetic saturation characteristics are included in the developed model. The no-load magnetic saturation characteristic curve shown in Table 1 was adopted to represent the example characteristics and used with a liner interpolation.

Table 1. No-load saturation characteristic curve.

Field Current (p.u.)	0	0.48	0.8	1.0	1.5	2.25
Terminal Voltage (p.u.)	0	0.5	0.82	1.0	1.11	1.20

By introducing the d - and q -axis mutual inductance current i_{md} (p.u.A) and i_{mq} (p.u.A) shown in (14) and (15), the unsaturated values of the d - and q -axis air-gap magnetic fluxes ϕ_{adu} and ϕ_{aqu} (p.u.Wb) are written as (16) and (17);

$$i_{md} = -i_d + i_{fd} + i_{kd}, \quad (14)$$

$$i_{mq} = -i_q + i_{kq}, \quad (15)$$

$$\phi_{adu} = L_{md} i_{md}, \quad (16)$$

$$\phi_{aqu} = L_{mq} i_{mq}. \quad (17)$$

The base values for the per unit system for the air-gap fluxes is the saturated value of the air-gap flux when the machine operates with no-load at the rated rotational speed and the rated generator terminal voltage.

The magnetomotive force H_g (p.u.A/m) induced by the current i_{md} and i_{mq} are given by

$$H_g = \sqrt{\phi_{adu}^2 + \phi_{aqu}^2}. \quad (18)$$

The internal induced voltage e_{gs} (p.u.V) considering the magnetic saturation can be obtained by referring the no-load magnetic saturation curve. Then the coefficients involving the saturation can be calculated by (19) and (20).

$$K_{s1} = e_{gs} / H_g \quad (19)$$

$$K_{s2} = 1 - K_{s1} \quad (20)$$

The saturated value of the d -axis mutual inductance $L_{m ds}$ (p.u.H) and the d -axis air-gap magnetic flux ϕ_{ads} (p.u.Wb) are derived by (21) and (22), respectively.

$$L_{m ds} = K_{s1} L_{m du} = L_{m du} - K_{s2} L_{m du} \quad (21)$$

$$\phi_{ads} = K_{s1} \phi_{adu} = \phi_{adu} - K_{s2} \phi_{adu} \quad (22)$$

In the developed model, it is assumed that the d - and q -axis air-gap magnetic flux decrease in proportional to the saturation coefficient K_{s1} compared to the unsaturated value. The second terms on the rightest sides of (21) and (22) represent the decrease amount due to the magnetic saturation.

2.4 Fluctuating mechanical torque of diesel engine

Waveform of mechanical torque of diesel engine generator and its possibility for voltage flicker was thoroughly investigated in [4]. It concluded that the misfiring of the diesel engine has caused the flicker in that case study.

Diesel engine is a kind of four-cycle internal combustion engines and the number of cylinders firing in each revolution N_F of the shaft is given by

$$N_F = N_C / 2, \tag{23}$$

where N_C is the number of cylinders. As for detail of the deriving the relation, refer to [4] and [5].

Among the common examples of the number of the poles, 6 and 8 are mentioned as the most sensitive frequencies for human perception in [4]. A diesel generator with 6 poles and 12 cylinders is considered in this study.

Some example waveforms of the engine torque are also available on [4]. The normalized engine torque for two revolutions shown in the Fig. 7 and the Table A.1, as well as the case engine torque with #7 misfiring in the Fig. 9 is used in the next section. The data of the Fig. 9 was derived by assuming the net torque of the misfiring cylinder to be zero; therefore, it is very large disturbance to the generator.

3. Simulation Results

The characteristics of the developed model were verified through some numerical simulations by use of XTAP.

3.1 Simulation conditions

The simulated system is shown in Fig. 1. A synchronous diesel generator model was connected to an infinite bus through a step-up transformer and long transmission lines. The step-up transformer was simulated by inductances, the infinite bus was by 3-phase sinusoidal voltage source. The mutual capacitances of transmission lines were neglected. The initial power flow condition and the per unit impedance are described in Fig. 1. The reference values of line voltage, capacity and frequency are 220 V, 100 kVA, and 60 Hz, respectively.

Generator constants are listed in Table 2. The base value of per unit system is the rated value of the generator: 220 V, 100 kVA, and 60 Hz. Since the one damper winding is considered in each of d - and q -axis circuit as mentioned above, there are no q -axis transient constants as L_q' and T_q' .

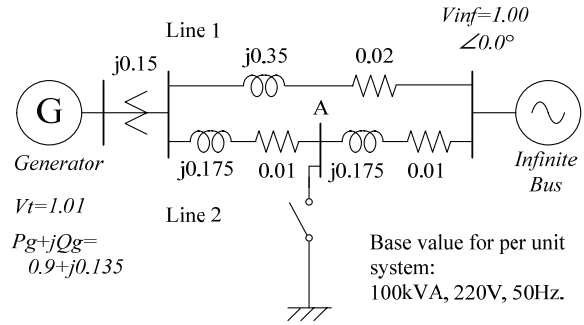


Fig. 1. Schematic diagram of the simulated power system

Table 2. Generator Constants

Symbol	Quantity	Value
M	unit inertia constant	1.00 s
L_d	d-axis synchronous inductance	1.65 p.u.
L_q	q-axis synchronous inductance	1.00 p.u.
L_d'	d-axis transient inductance	0.35 p.u.
L_d''	d-axis sub-transient inductance	0.25 p.u.
L_q''	q-axis sub-transient inductance	0.25 p.u.
L_l	armature leakage inductance	0.225 p.u.
T_d'	d-axis transient short circuit time constant	0.80 s
T_d''	d-axis sub-transient short circuit time constant	0.035 s
T_q''	q-axis sub-transient short circuit time constant	0.035 s
T_a	armature time constant	0.1 s
D	generator damping coefficient	0.0 p.u.

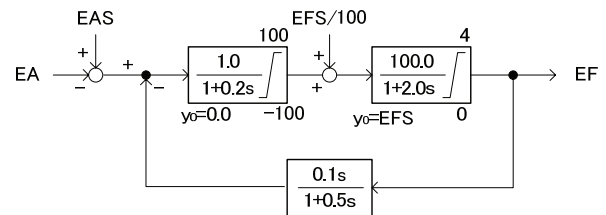


Fig. 2. Block diagram of the AVR used in the simulation

The generator was equipped with AVR and speed governor (GOV). Fig. 2 exhibits the block diagram of the AVR. It is one of the standard AVR models used for the power system analysis in Japan. The characteristic of the GOV was simply expressed by (24), where T_{m0} is the initial value of the mechanical torque. T_m is the main body of the engine torque. The oscillation due to firing of cylinders was simulated as coefficients times to T_m .

$$T_m = T_{m0} / \omega_r \tag{24}$$

It should be noted that there are many variations in characteristics of actual AVRs and GOVs for diesel engine generators. The individual controller model should be used when this diesel generator model is used for analyses.

3.2 Simulation results of fluctuating engine torque

Fig. 3 shows the simulated engine torque. The waveform was composed by combination of sinusoidal waves.

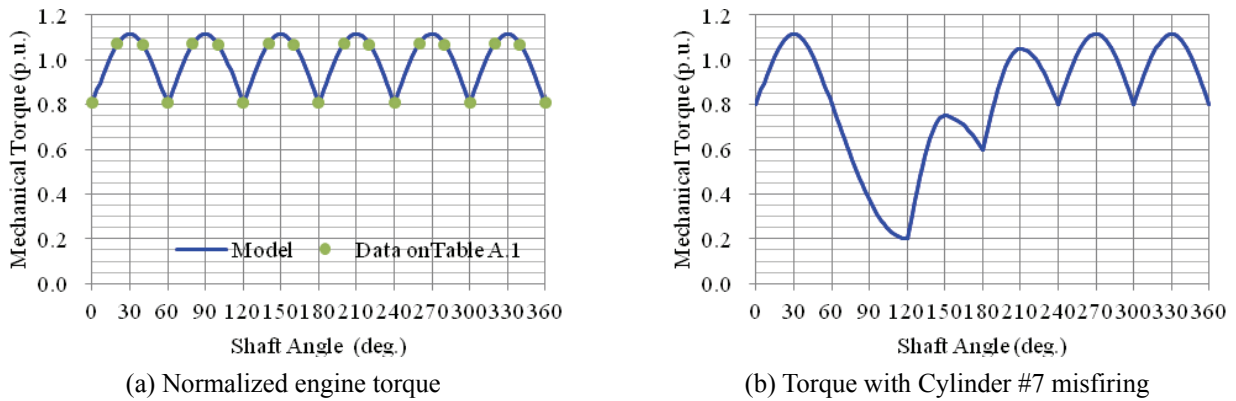


Fig. 3. Simulation results of engine torque

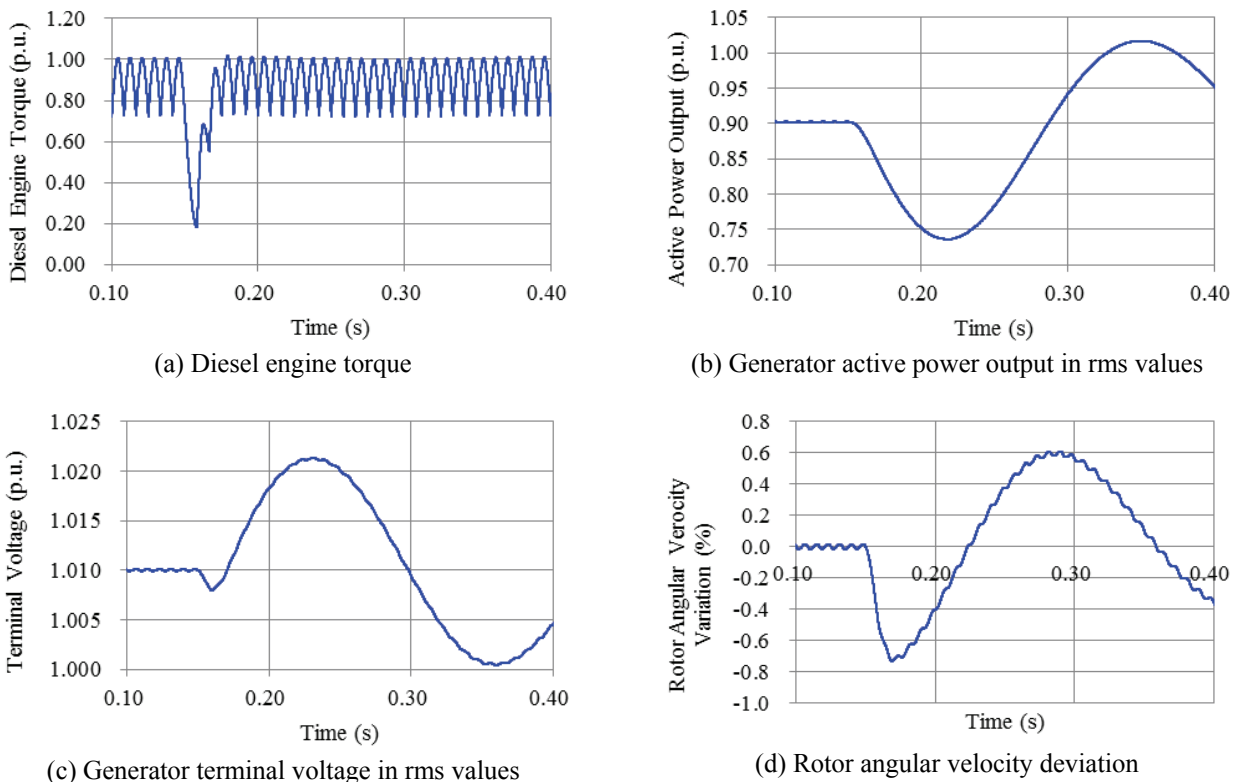


Fig. 4. Simulation results for the torque variation

Fig. 3 (a) exhibits the composed engine torque accords with the data in [4]. Fig. 3 (b) shows the engine torque with misfiring of Cylinder #7.

Fig. 4 exhibits the simulation results with engine torque oscillation.

Fig. 4 (a) shows the waveform of the simulated torque. The large sag in the torque is caused by the misfiring of cylinder #7.

Fig. 4 (b) describes the resulting large disturbance in the generator active power output. The result indicates that the misfiring of cylinders may cause not only voltage flickers but also change in active power output and might leads to stability problem in a remote weak power system.

Fig. 4 (c) shows the generator terminal voltage. Before

the misfiring, small oscillations due to normal mechanical torque fluctuation was successfully simulated. The voltage dropped by the misfiring and largely changed due to the active power imbalance.

In Fig. 4 (d), the rotor angular velocity variation and the oscillation due to the torque variation was observed. To simulate these oscillations in the shafts is also important to develop generator control systems such as GOVs and excitation control systems with the consideration of shaft noise.

3.3 Simulation results of generator variables

Fig. 5 exhibits the simulation results of generator

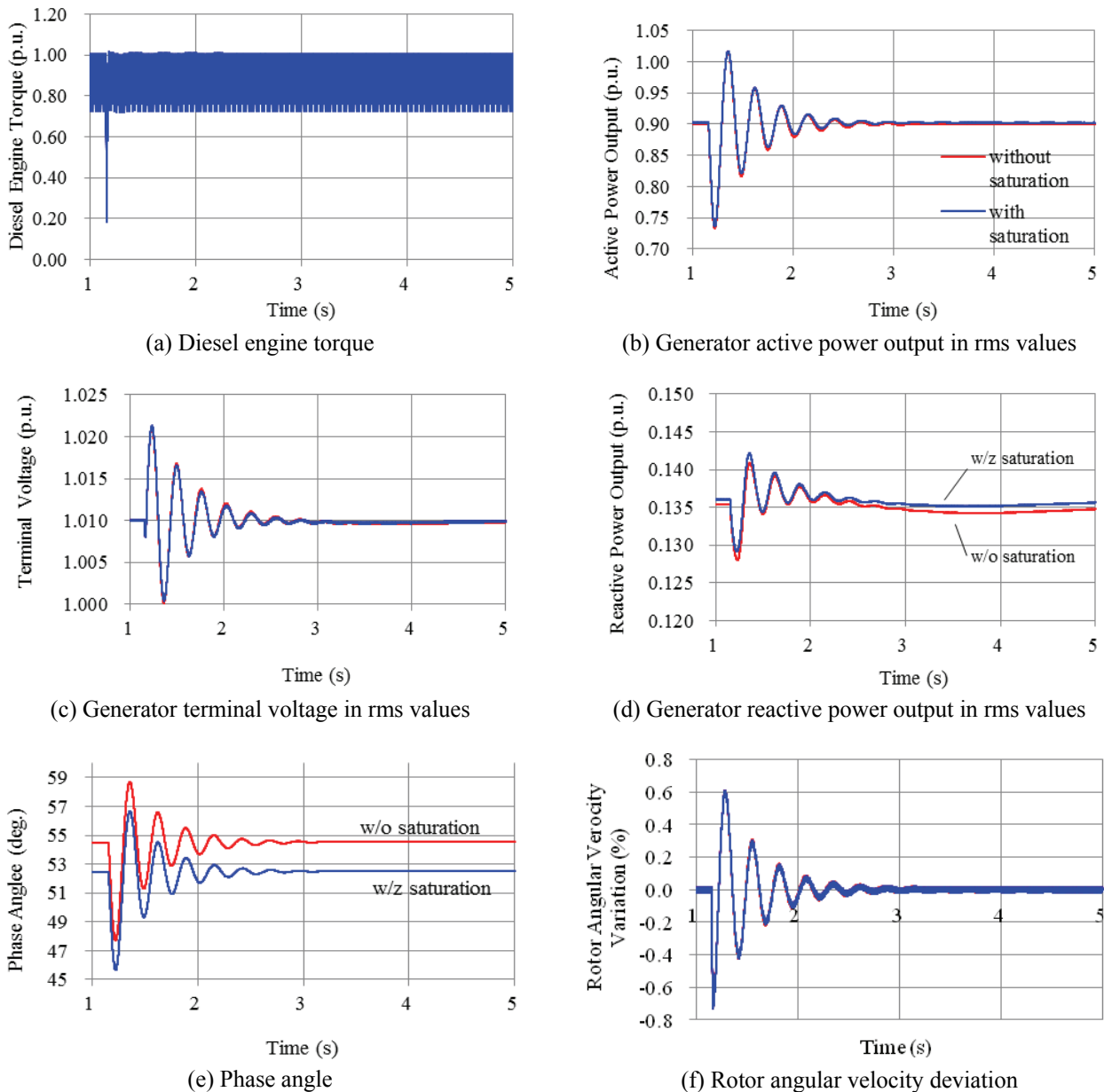


Fig. 5. Simulation results of generator variables.

variables for 1 to 5 seconds to the engine torque oscillation including cylinder #7's misfiring.

Fig. 5 (a) shows the waveform of the applied fluctuating engine torque. The misfiring causes disturbances to the power system as seen in the figures.

The effect of magnetic saturation was checked through the numerical simulations. The red lines in Fig. 5 (b) to (f) show the results considering the magnetic saturation, and the blue lines, the results without considering saturation.

Among these simulations, the same reference values were given for the generator active power of $P_g=0.9$ (p.u.W) and the generator terminal voltage $V_t=1.01$ (p.u.V) as seen in Fig. 5 (b) and 5 (c), respectively.

There are seen small differences between with and without saturation in the generator reactive power (Fig.

5 (d)) and the phase angle (Fig. 5 (e)). The difference due to magnetic saturation in the internal electromotive force led to these results. In this simulation, the unsaturated case was simulated only by letting the saturation coefficient $K_{s1}=1.0$ in order to check the results of applying the coefficient K_{s1} and K_{s2} . Therefore, when the saturation is considered, the phase angle became smaller and the system become slightly stable compared to the unsaturated case. The results will vary if the unsaturated case is simulated by using the saturated values of generator constants.

On the other hand, little difference are seen in the variables involving the balance of the input and output torques such as the active power (Fig. 5 (b)) and the rotor angular velocity (Fig. 5 (f)) for this case.

Through these numerical simulations, it is confirmed that the developed diesel generator model can simulate fluctuating engine torque and magnetic saturation, and contribute to EMT simulations to assess effects of these phenomena to electric power quality. Investigation of these assessments in small remote sites or islanded power systems with several diesel engine generators using the developed model is a future work.



Orie Sakamoto She received her B.S., M.S., and Ph.D degree from the University of Tokyo, Tokyo, Japan, in 2001, 2003, and 2006, respectively. Her areas of interest include modeling and control of synchronous generators and power systems including solar and wind power generations. She is a

member of IEEJ and IEEE.

4. Conclusion

In this study, the new diesel generator model with example fluctuating engine torque was developed for transient analyses using XTAP. The magnetic saturation characteristics were also included.

It was verified through the numerical simulations and comparison with the previous study that the model can simulate fluctuations in its terminal voltage and active power output due to the variation of engine torque.

The developed model is considered to be useful for analyses of small power systems with diesel generators. Effects of various fluctuating engine torque to electric power quality in remote sites or small islanded power systems should be investigated as a future work.

Acknowledgements

This work was partly supported by research grant from Japan Power Academy.

References

- [1] T. Noda, T. Takenaka, and T. Inoue, "Numerical Integration by the 2-Stage Diagonally Implicit Runge-Kutta Method for Electromagnetic Transient Simulations", *IEEE Trans. Power Delivery*, vol. 24, no. 1, pp. 390-399, Jan. 2009.
- [2] T. Noda and T. Kikuma, "A Robust and Efficient Iterative Scheme for the EMT Simulations of Non-linear Circuits", *IEEE Trans. Power Delivery*, vol. 26, no. 2, pp. 1030-1038, April, 2011.
- [3] T. Noda and K. Takenaka, "A Practical Steady-State Initialization Method for Electromagnetic Transient Simulations", *Proc. International Conference of Power Systems Transients (IPST2011)* in Delft, the Netherlands, June 14-17, 2011. Available: <http://www.ipst.org/>
- [4] P. M. Anderson, and M. Mirheydar, "Analysis of a diesel-engine driven generating unit and the possibility for voltage flicker", *IEEE Trans. Energy Conversion*, vol. 10, no. 1, pp. 37-47, March, 1995.
- [5] I. Boldea, "Synchronous Generators", CRC Press, 2005, pp. 3-12-3-15.