Global Scientific JOURNALS

GSJ: Volume 11, Issue 3, March 2023, Online: ISSN 2320-9186
www.globalscientificjournal.com

DIESEL GENERATOR SET TEST SETUP AND MODELING OF CONVENTIONAL GENERATING SETS

[1]Sylvester Emeka Abonyi, [1]Ugochukwu E Anionovo, [2]Odeh Calistus Princewill.
[1]Electrical Engineering Nnamdi Azikiwe University Awka
[2]Mechanical Engineering Nnamdi Azikiwe University Awka
s.abonyi@unizik.edu.ng, cp..odeh@unizik.edu.ng, ue.anionovo@unizik.edu.
Corresponding author. s.abonyi@unizik.edu.ng.

Abstract.

This paper described the diesel generator set test setup and modelling of conventional generating sets. A Mikano generator set (Model no. Sp 60), 10kAV was used. The output of the brushless exciter is rectified using a diode bridge that is placed on the shaft and is commonly known as a flying rectifier arrangement. The output of the rectifier bridge is connected to the field winding of the main synchronous machine. The parameter for synchronous machines was obtained from Mikano data base. Test results step load and voltage changes were obtained. Electromagnetic Transient Program (EMTP) model of Internal Combustion (IC) engine based generating set model was developed in EMTP simulation platform. The simulated speed waveforms for an 8kW step load change was compares with the measured hardware response for the same change. Results showed a good match between the waveforms.

Keywords: *Diesel generator, brushless, exciter, synchronous machines, EMTP*.

Introduction

Diesel generator sets are widely used for independence power supply, especially where power grids are not accessible or where power backup is required for increase of customer electro-safety. There are medium and high power generator sets used for power supply of hard-to-reach regions, in military and civil transport with electric powertrains, in electric generation stations as well as for energy backup in medical, governmental and other facilities are of primary concern.

The effect of the use of generator set to the environment are had been on the increase tremendously, this has resulted to high requirements to their operation. The requirements are increasingly restricted to reliability (especially for strategically important facilities), noise protection, precision, transients as well as fuel, economy and ecological quantities.

In general, there are two ways of diesel-electric sets development. The first way is related to improvement of the construction of engines and generators: the geometry of the air, fuel and oil delivery systems, exhaust gas disposal system, electric circuits and rotating parts of engines/generators, etc. The second way is involved with improvement of diesel-generators control systems regulating the output frequency and voltage, and indicating emergencies. [1] A major breakthrough to development of diesel-generators was due to implementation and improvement of microprocessor-based systems that permitted to design arbitrary complex and efficient control laws taking into account construction features, generator dynamics and environment conditions. [2]

Diesel-electric generator sets are complex nonlinear systems consisting of many subsystems and units and operate in presence of loads and disturbances. A number of variables characterizing the motion of diesel-generator sets is subjected to amplitude and phase distortions. Some variables cannot be measured directly and can only be evaluated. In this regard, to increase the efficiency of diesel-generator sets we have to accurately predict its dynamics and evaluate the speed, voltage and frequency responses to input signals (controls, load and disturbances) and design features.

Linear models are oriented to design of engine speed and air-to-fuel ratio control via well-known and highly developed classical theory of linear systems [2, 4]. Each local control provides required performance within a regime corresponding to some range of pressures, speeds, delivery begin angles, etc. Despite the simplicity of control structure and relatively high performance of local controls, design of the whole sets of both local models and controls can be a laborious procedure and can be essentially complicated due to increasing requirements to control system performance.

Nonlinear physical models are based on fundamental physical laws and are represented in the form of nonlinear differential equations connecting control variables and disturbances together with regulated and state variables [5]. Since the model design is physically motivated, there is every reason to believe that the derived control will be implementable in practice. Turbine and compressor efficiency, delivery begin efficiency, fuel-to-air ratio, combustion efficiency, friction torque and other characteristics are evaluated in the same way and the characteristics are averaged and assumed constants what leads to the loss of model performance.

Empirical models are represented as abstract structures with parameters calculated experimentally during preliminary or adaptive (online) identification [6, 7]. As an example, an artificial neural network or a linear regressive model can be considered. A suitable choice of the structure and parameters identification permit to improve the model performance without detailed investigation of engine processes [8, 9]. At the same time calculation of the model parameters requires teaching sample of experimental data that covers all possible regimes of diesel engine operating. Besides, the abstract structure usually does not permit direct derivation of physically implementable control law. Exception to this are so called inverse models [10] that are also empirical and are taught over the same data sample. These models are usually used for implementation of feed forward loop in a control law

The structural design of a typical diesel generating set with a wound field synchronous machine is shown in Fig. 1.

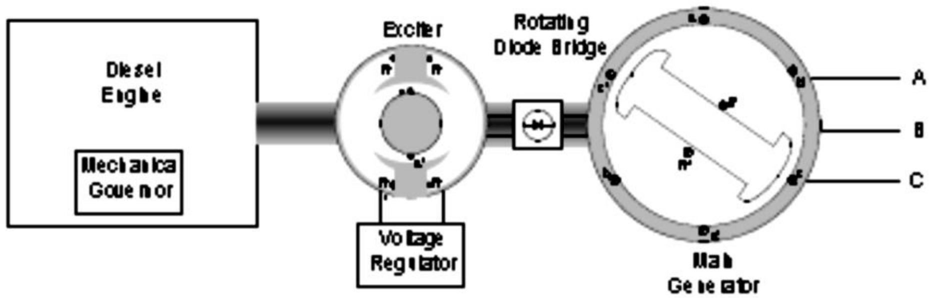


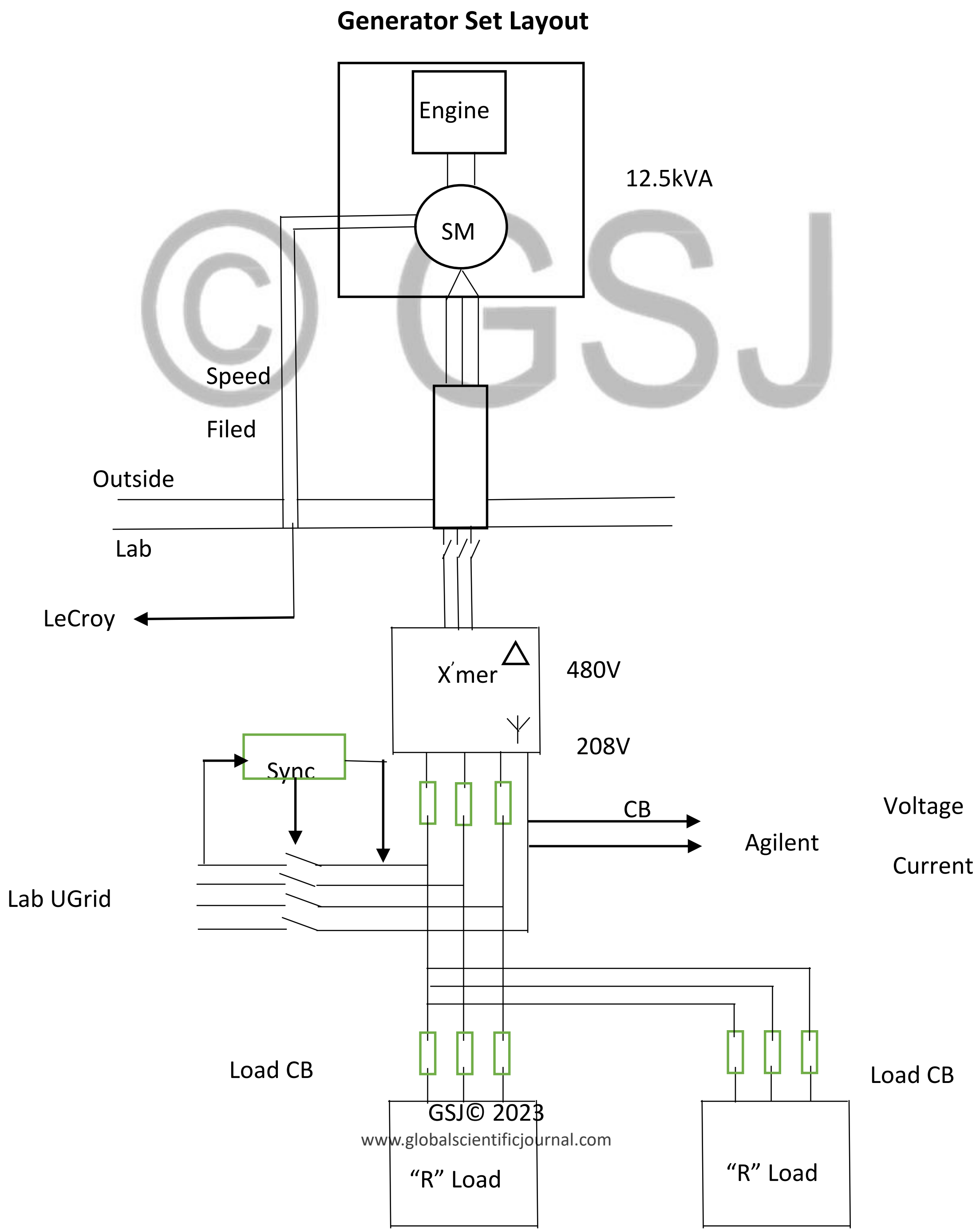
Fig. 1: Configuration of Mikano 10kW diesel generator set system. [11].

The engine governor could either be mechanical or electronic in nature. Most small generator sets with rating less than 10kW, typically have mechanical governors to minimize the cost of the system. The synchronous generators are coupled to the engines and their field winding are powered by a separate exciters machines. There are various exciter configurations possible and the most common structure consists of a brushless exciter. By varying the input DC voltage of the brushless exciter the filed winding of the main synchronous machine is controlled. The PWM switching does the work of varying the field winding voltage desired to a desired value.

To fixed voltage that can be modified by the user a generating set operating in an islanded mode is setup. A model that captures the required dynamics behavior of the diesel generating set in a micro-grid environment is necessary. The model for the diesel generating set was developed by studying its behavior in an islanded environment. To develop this model a 10kW diesel generating set manufactured by power diesel was installed at Nnamdi Azikiwe University Awka, Anambra State Nigeria. This work describes the test setup and the hardware test results used in developing the generating set model.

2. Hardware components and system configuration

The Mikano generating set (Model no. Sp 60) consists of a 10kW diesel engine coupled to a wound field synchronous machine. The speed regulator in the generating set is a mechanical governor and the exciter is of the brushless type having a single phase output. A voltage regulator provides the input to the brushless exciter using a standard 12V battery supply. The connection diagram for the Perkins generator set is shown in Fig. 2.


Generator Set Layout
Engine
12.5kVA
SM
Speed
Filed
Outside
Lab
LeCroy
X′mer
480V
208V
Sync
CB
Voltage
Agilent
Current
Lab UGrid
Load CB
Load CB
“R” Load
“R” Load

ISSN 2320-9186

Fig. 2: Diesel generating set test setup at the Nnamdi Azikiwe University Awka

The Perkins generating set is mounted outdoors on a grating adjacent to the main Engineering lab as shown in Fig. 3 and Fig. 4. The windings of the generator have been connected to provide 480V line to line rms voltage. This was done using the winding diagram provided in the operations manual of the generating set. The output of the generator is brought into the lab using gauge 12 wires into a disconnect switch. Number # 4 wires then carry the power to a 45 kVA ΔY transformer. The transformer steps the voltage down from 480V to 208V line to line. Resistor banks are connected at the secondary of the transformer to load the machine.

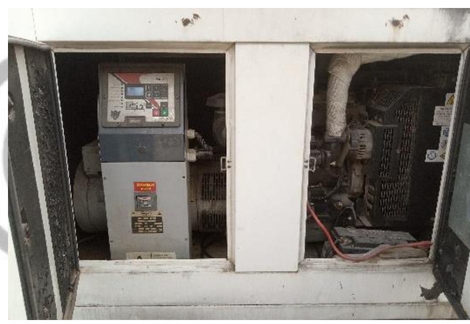


Fig. 3: Test setup for Mikano 10kW generating set located outside engineering laboratory.

Fig. 4: Picture of diesel engine used in 10kW Mikano generator

The parameters for the synchronous machine were obtained from Perkins are given in Table 1

Table 1. Parameters for synchronous machine in Mikano Sp 60 generator.

ISSN 2320-9186

Parameters	Values
V_{base}	240V
P_{base}	125kVA
x_d	1.204pu
x_q	0.533pu
x'_d	0.125pu
x''_d	0.056pu
x''_q	0.051pu
x_l	0.037pu
T'_{do}	0.355s
T''_{do}	0.00015s
T''_{qo}	1.235s
J	0.4344kgm^2

3. Test results for step load and voltage changes.

A series of step load tests were performed to determine the characteristics of the diesel generator set. The load connected to the machine was changed by 8kW and the shaft speed, terminal voltage, current and brushless exciter input voltage were measured using an Agilent scope and they are plotted in Fig. 5. The pulsed output of the speed sensor was converted to a speed signal via post processing and the resulting waveforms are plotted in Fig. 6.

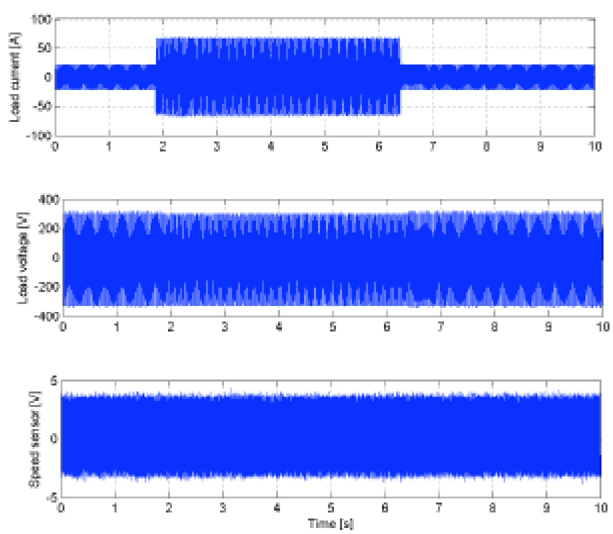


Fig. 5: Results for 8kW load switching

ISSN 2320-9186

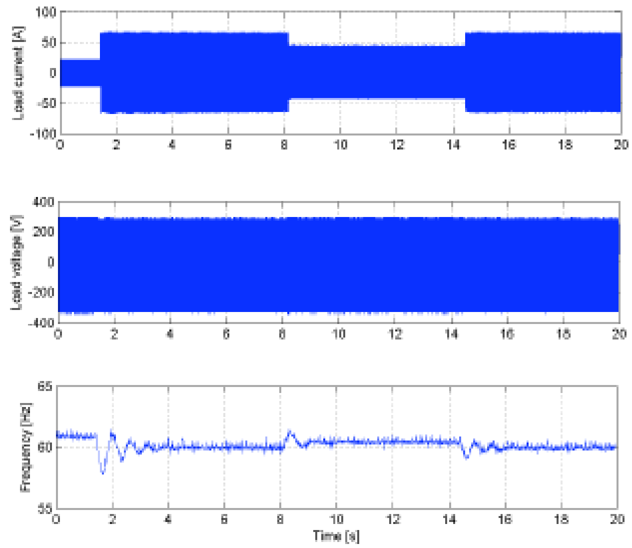


Fig. 6: Results for 8kW load switching waveform depicting change in frequency

From the waveforms we can clearly see that there is a change in the steady state frequency with loading. The change in frequency is consistent with the manufacturer specified droop value of 5%. We can also see the second order dynamics of the mechanical governor in the speed waveform. We can also see that during the transient the load voltage waveform regains its steady state value within a few cycles. The voltage regulator provided by the manufacturer has a V/Hz component that changes the terminal voltage based on the shaft speed. The V/Hz component is required to improve the motor starting capability of the generating set. Hence in steady state at lower speed (for the higher load) the terminal voltage is slightly lower that at higher speed. The contribution of the per unit speed to per unit terminal voltage was calculated to be close to 1%. These conclusions were confirmed by performing another load test with a 2kW step change and the waveforms obtained are plotted in Fig. 7 and Fig. 8.

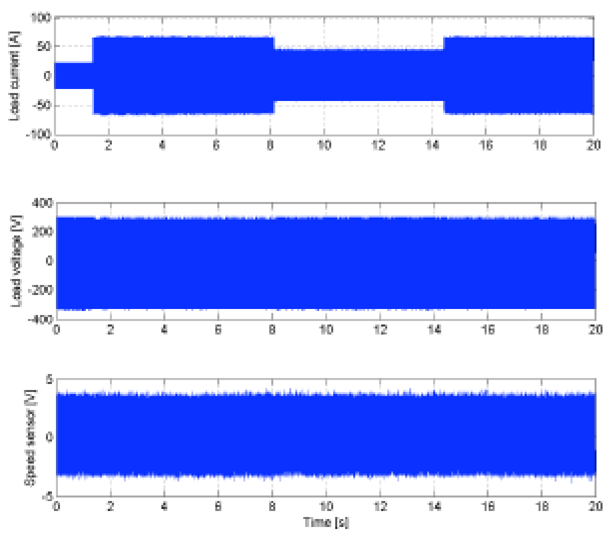


Fig. 7: Results for 8kW load increase followed by 4kW decrease and increase in load

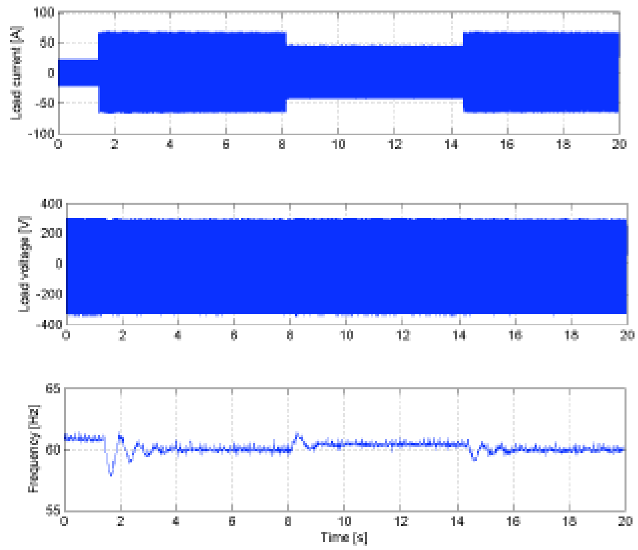


Fig. 8: Results for 8kW load increase followed by 4kW decrease and increase in load with

4. Electromagnetic Transient Program (EMTP) model of Internal Combustion (IC) engine based generating set model

Using the models for each component a model of the generating set system was developed in the EMTP simulation platform [12]. EMTP is a sophisticated computer program for the simulation of electromagnetic, electromechanical and control systems transients in multiphase electric power systems. It features a wide variety of modeling capabilities encompassing electromagnetic and electromechanical oscillations ranging in duration from microseconds to seconds. This enables the simulation of the generator set in a micro grid environment. The lab setup shown previously in Fig. 2 is represented in EMTP as shown in Fig. 9.

Mikano Genset Model

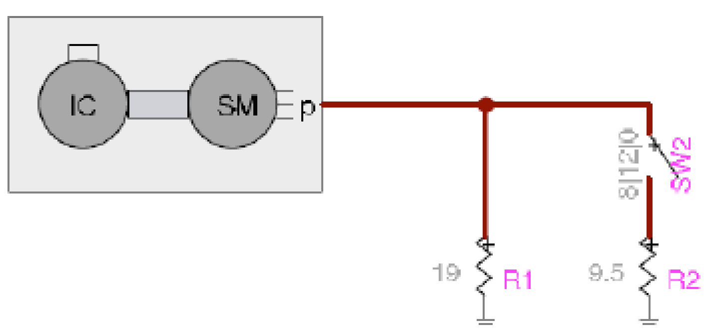


Fig. 9: Lab setup modeled in EMTP

Mikano Genset Model

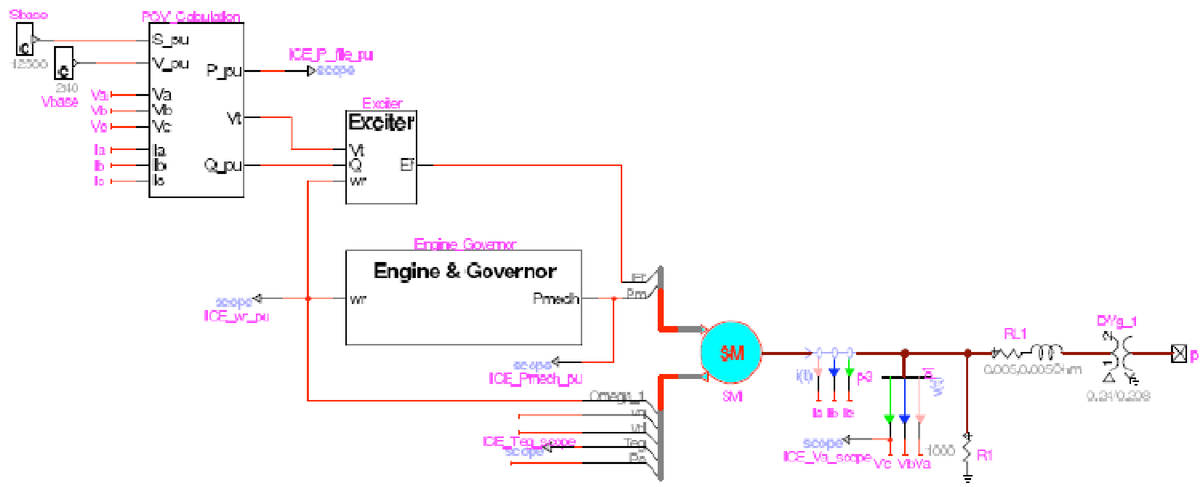


Fig. 10: Internal model of diesel generator set in EMTP

If we examine the model of the generator set (Fig. 1) more closely we can see that it consists of four sub-blocks.

i. Synchronous machine ii. P, Q and V calculation block, iii. Exciter block. iv. Governor and Prime Mover Block

The output terminals of the synchronous machine are connected to a 45kVA transformer using a line impedance. A parallel resistive load of negligible value is connected at the synchronous machine terminals to alleviate numerical problems associated with disconnecting the synchronous machine from the rest of the system.

The synchronous machine model used is from the machines library of EMTP. While setting up the model we need to specify one damper in field axis circuit and one damper in the q axis circuit. To obtain a salient pole machine we set Tq0 $'x_q = x'_q \quad and \quad T_{q0}' = 0$. We use maximum precision in the precision tab of the machine model and increase the number of maximum rotor speed iterations to 1000 to overcome numerical problems.

The inertia of the machine is 0.19s and is calculated from the value specified by Mikano and is given in Table 1. The remaining electrical parameters are fed in the various tabs using the values given in Table 1. Also for simulation purposes the machine base voltage was specified as 240V and the transformer was modeled as a 240V/208V DYg transformer. Mikano also specified the exciter machine to have a time constant of 1ms and that the voltage regulator was a PI controller. The voltage regulator has the following three control potentiometers:

i. Volts/Hz setting. ii. ΔV Setting iii. Controller gain setting

For the exciter the reference voltage set point has two components:

i. Speed dependent term ii. Fixed reference point with ΔV control.

The three phase terminal voltages of the machine are rectified and filtered and passed to the exciter as the measured voltage. The difference between reference voltage and measured voltage is fed to a PI controller as shown Fig. 11. The gain values Kp and Ki for the controller were set to mimic the dynamic performance observed in the hardware. During a transient change the variation in voltage was fairly negligible and this can be attributed to a high gain setting.

Exciter model of Mikano Genset

Input: Filtered terminal voltage in pu; Rotor speed for V/Hz component, Filtered reactive power for QV droop; voltage reference point of QV droop.

Output: fied voltage in pu

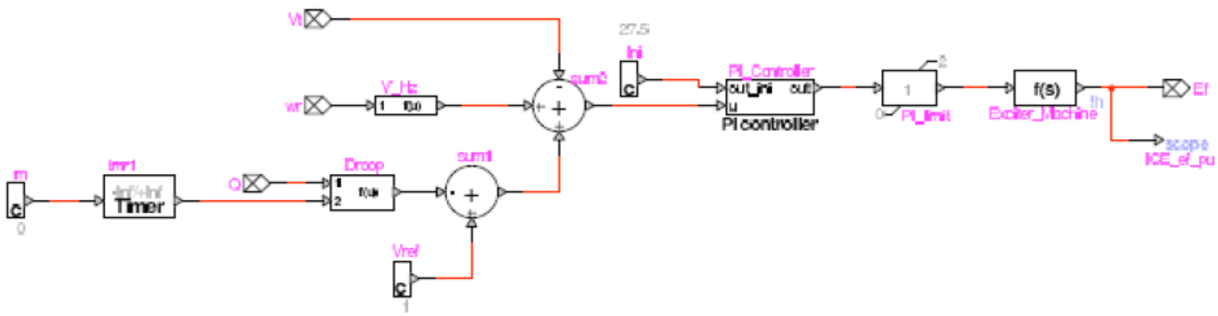


Fig. 11: Model of exciter and voltage regulator in EMTP

The desired field voltage obtained from the PI controller is passed through a time constant which describes the exciter machine. The exciter machine is configured with a DC field in the stator and a single phase winding on the rotor. The output of the exciter machine is rectified and fed to the main field of the machine. The rectifier arrangement is not modeled and instead the time constant represents the whole exciter and brush arrangement. The exciter provides the field voltage required for the main field of the synchronous machine.

The voltage regulator utilizes the terminal voltage and reactive power values calculated from the PQV calculation block and the per unit rotor speed. The reactive power is needed only for modifying the reference voltage command to incorporate QV droop. The Kohler generator set does not incorporate QV droop and hence the value of droop is set to zero. The initial value of the PI controller output is set to minimize the startup transient. The per unit rotor speed deviation also contributes to the reference voltage calculation. From experimental tests the contribution was calculated to be equal to 0.01. The exciter machine is represented as a first order system with a time constant of 1ms (specified by Perkins). Typically machines with ratings less than 100 kW can be represented using either first order or second order systems instead of the more complex standard IEEE exciter definitions.

The mechanical governor utilizes the speed of the shaft to determine the opening and closing of a fuel valve. The combined dynamics of the governor, fuel actuator and combustion dynamics are represented by a second order lead-lag transfer function. A time delay further represents the engine dynamics. The governor used in the generator set is mechanical in nature and provides for a 5% drop from no load to full load. The governor provides the mechanical power required by the

ISSN 2320-9186

synchronous machine. The governor and engine model uses the rotor speed as its input. The rotor speed is used with the 5% droop to determine the required engine torque. This torque command is passed through a lead lag transfer function and then through the combustion time delay. The torque value is then multiplied by the rotor speed to calculate the mechanical input power.

Detailed Governor and prime mover for Mikano Genset

Input: Rotor speed, Governor Reference Power

Output: Mechanical input in pu

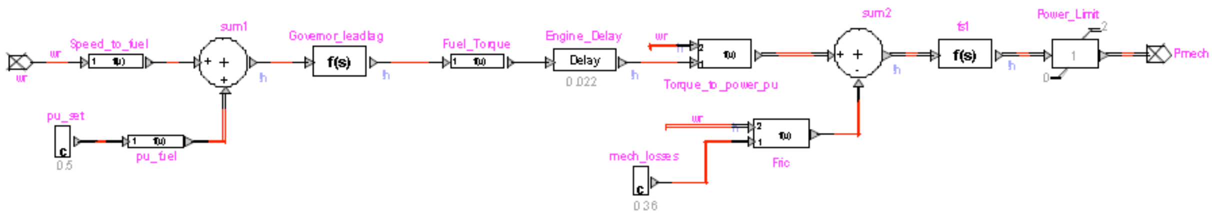


Fig. 12: Governor and IC engine model in EMTP

5. Discussion and conclusion

The developed model with its tuned gains was verified by simulating a step load change and comparing the results with the experimental results obtained in the hardware run. Fig. 13 shows the simulated speed waveforms for an 8kW step load change and compares it with the measured hardware response for the same change. From Fig. 13 we can see that we have a good match between the waveforms. Similar results were obtained for the 4kW step load change as well.

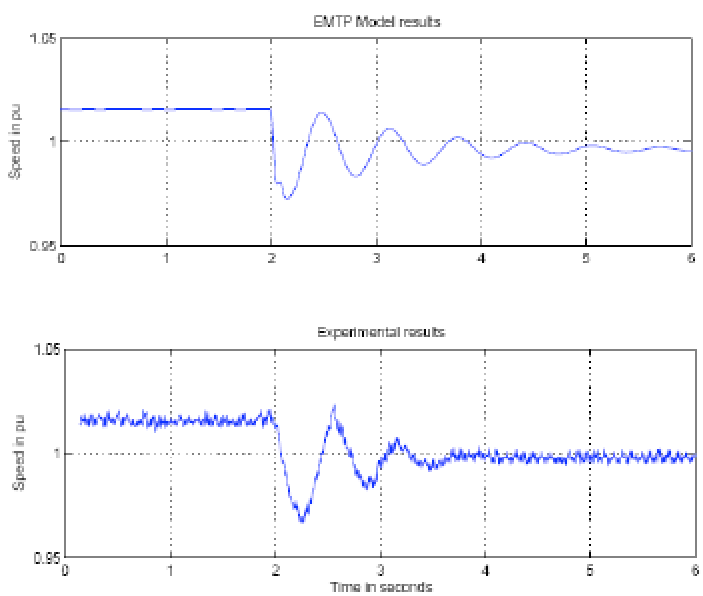


Fig. 13: Comparison of simulated and values of speed for step 8kW load change

The work described the test setup for an IC engine based generating set at the Nnamdi Azikiwe University Awka. Test results for step load changes can be characterize the mechanical governor of the generator.

Reference

[1]. M. E. Belyaeva, D. N. Gerasimova, M. R. Rymalisb, and S. A. Semenovc. Design of Diesel Engine Mathematical Model Oriented to Speed Control. Journal of Computer and Systems Sciences International, 2018 25th Auust, Vol. 57, No. 4, pp. 626–639

[2]. V. V. Furman, V. A. Ivanov, and V. A. Markov. "Electronic control systems for diesel engines," Inzhen. Zh. Nauka Innov. 2013

[3]. Landhäußer, F. *et al.* (2014). Electronic Diesel Control (EDC). In: Reif, K. (eds) Diesel Engine Management. Bosch Professional Automotive Information. Springer Vieweg, Wiesbaden. https://doi.org/10.1007/978-3-658-03981-3_20

[4]. J. Wahlström and L. Eriksson. "Modeling diesel engines with a variable-geometry turbocharger and exhaust gas recirculation by optimization of model parameters for capturing nonlinear system dynamics," 2011 Volume 225, Issue 7, https://doi.org/10.1177/0954407011398177

[5]. Gerasimov, D. N., et al. "Injection engine as a control object. II. Problems of automatic control of the engine." *Journal of Computer and Systems Sciences International* (2010) 23rd Dec.: 49 998-1008. https://doi.org/10.1134/S1064230710060183

[6] Sergey Samokhin *, Teemu Sarjovaara **, Kai Zenger *, Martti Larmi. Modeling and Control of Diesel Engines with a High-Pressure Exhaust Gas Recirculation System, Volume 47, Issue 3, 2014, Pages 3006-3011. https://doi.org/10.3182/20140824-6-ZA-1003.02231

[7] D. N. Gerasimov, M. E. Belyaev, V. O. Nikiforov, H. Javaherian, S. Li and Y. Hu, "Inverse adaptive air-fuel ratio control in spark ignition engines," *2016 European Control Conference (ECC)*, Aalborg, Denmark, 2016, pp. 1253-1258, doi: 10.1109/ECC.2016.7810461.

[8]. Yildiray Yildiz,a, Anuradha M. Annaswamya , Diana Yanakievb , Ilya Kolmanovskyb. Spark Ignition Engine Fuel-to-Air Ratio Control: An Adaptive Control Approach. June 8, 2009. Pp 1-40, https://doi.org/10.1016/j.conengprac.2010.06.011

[9]. G. Kushwaha and S. Saraswati. "Air path identification of turbocharged diesel engine using RNN," in Proceedings of the International Conference on Industrial Instrumentation and Control ICIC, Pune, India, 2015 pp. 1328– 1332.

[10]. K Nikzadfar* and A H Shamekhi . Developing a state space model for a turbocharged diesel engine using the subspace identification method. Automobile Engineering Proc. IMechE Vol. 225 18 May 2011. Pp 1692-1704

[11]. S. Kim, H. Jin, and S. B. Choi. "Exhaust pressure estimation for diesel engines equipped with dual-loop EGR and VGT," IEEE Trans. Control Syst. Technol. 2017 99, 1–11.

[12]. EMTP-RV simulation platform, www.emtp.com