

The Numerical Modeling of Transient Regimes of Diesel Generator Sets

Tiberiu Tudorache, Cristian Roman

Electrical Engineering Faculty, University Politehnica of Bucharest
313 Splaiul Independentei, Sect. 6, Bucharest, Romania
e-mail: tudorach@amotion.pub.ro

Abstract: This paper deals with the numerical modeling of a diesel generator set used as a main energy source in isolated areas and as a back-up energy source in the case of renewable energy systems. The numerical models are developed using a Matlab/Simulink software package and they prove to be a powerful tool for the computer aided design of complex hybrid power systems. Several operation regimes of the equipment are studied. The numerical study is completed with experimental measurements on a Kipor type diesel-electric generator set.

Keywords: Diesel generator set; numerical models; experimental analysis

1 Introduction

The increasing demand for energy, the continuous reduction in existent resources of fossil fuels and the growing concern regarding environmental pollution have compelled mankind to explore new production technologies for electrical energy using clean renewable sources such as wind energy, solar energy, etc.

Among the electric power technologies using renewable sources, those based on the conversion of solar and wind energy are clean, silent and reliable, with low maintenance costs and small ecological impact. Sunlight and the kinetic energy of the wind are free, practically inexhaustible, and involve no polluting residues or greenhouse gases emission. Along with these advantages, however, electric power production systems using as primary sources exclusively solar and wind energy pose technical problems due to uncontrollable wind speed fluctuations and to the day – night and summer – winter alternations. As a consequence, in autonomous regimes, the power supply continuity of a local grid should be backed-up by other reliable and non-fluctuant sources of primary energy, such as diesel generator sets. Such systems, designed for the decentralized production of electric power using combined sources of primary energy, are called hybrid systems.

By combining several renewable energy sources (wind/PV/diesel), a hybrid system may ensure increased reliability in the electric power supply to consumers, at optimum quality parameters, in the condition of a minimum required electric power during an imposed time period.

The increased interest in using diesel generator sets as the main energy source in isolated areas or as an emergency source in the case of renewable-based power systems can be observed by the great number of papers and studies carried out in this area. The research conducted in this domain refers to aspects such as: island operations of diesel generator sets [1], simulations of diesel/pv/wind hybrid power systems [2]-[3], numerical modelings using special regulation techniques such as neural networks and fuzzy logic [4]-[6], etc. Various aspects about these regulation techniques can be found also in [7]-[8].

The topic proposed in this paper refers to the development of numerical models for the simulation of the operation regimes of diesel generators integrated as a back-up energy source in hybrid power systems as back-up energy source. The numerical analysis is completed by experimental investigations on a Kipor type diesel generator.

2 Diesel Generator Sets

Diesel generator sets convert fuel energy (diesel or bio-diesel) into mechanical energy by means of an internal combustion engine, and then into electric energy by means of an electric machine working as generator.

2.1 The Main Parts and Characteristics of Diesel Generator Sets

The main parts of a diesel generator are: the internal combustion engine, usually air- or water-cooled; the electric generator usually of synchronous type; the mechanical coupling; the support chassis; the battery for generator start-up; the fuel tank; the starter motor; the command panel, etc.

The main characteristics of a diesel generator set are: rated power, rated voltage, rated frequency, number of phases, etc.

The diesel generator sets are usually designed to run at 3000 rpm or 1500 rpm at a frequency of 50 Hz. The primary movers are internal combustion engines equipped with mechanical regulators to keep the imposed speed, integrated in the injection pump and adjusted to obtain an output frequency of about 52 Hz without load and 50 Hz for rated load.

The proper operation of a diesel generator set is determined to a great extent by two main components, the *speed regulator* and the *voltage regulator*. The performance of these components are vital for the operation and utilization of diesel generator sets, their purpose being to precisely maintain the imposed parameters of electric power (voltage and frequency).

The *speed regulator* is designed to keep constant the internal combustion engine speed by changing the quantity of fuel consumed by the motor. The direct result of this speed regulation is a stable frequency of voltage at the generator terminals (since frequency is proportional to the generator speed). A constant frequency requires good precision and a short response time from the speed regulator. The speed regulator starts regulating when various electric loads are connected or disconnected at the generator terminals.

There are a lot of speed regulation systems, starting from the simpler spring-based ones up to complex hydraulic and electronic ones able to regulate dynamically the fuel admission valve to keep the speed constant in a given range with response times at load changes smaller than 1-3 seconds.

The main role of the *voltage regulator* is to control the voltage at the generator terminals and to keep it constant by limiting as fast as possible the voltage peaks and over voltages that occur due to load variations. The quantity that the voltage regulator acts on is the excitation current that changes the voltage amplitude at the generator terminals.

2.2 Utilizations of Diesel Generator Sets

Diesel generator sets are equipment that work either in *isolated regime*, in areas where there is no possibility to connect to the grid (e.g. the electric energy supply of households, chalets, holiday houses, isolated objectives, equipment in industrial sites, electric installations for outdoor entertainment events, military equipment, telecommunications, etc.), or as *emergency regime*, as a reserve electric power source, in the event of electric power blackouts. In *emergency regime* the diesel generator sets usually supply only vital consumers, like fire pumps, elevators, safety lighting installations, banks, hospitals, government buildings, offices, supermarkets and large restaurants, hotels, malls, stadiums, airports, fuel stations, private houses, and industrial sites where specific processes do not allow for blackouts, become uncontrollable or generate important losses without electric power, etc.

Usually, in parallel with diesel generator sets, UPS systems are used, with a buffer role, able to ensure for short periods the continuity of power supply for vital consumers, until the diesel generator sets are started-up. The minimum combined time necessary for the detection of a grid voltage drop, the start-up of internal combustion engine, reaching the stabilized regime of the generator (frequency and voltage) and the load connection is typically at least 10-15 seconds.

In the case of power systems based on renewable energies, given the fluctuant character of unconventional energy sources (e.g. wind or solar energy), diesel generator sets takes on particular importance, their role being to ensure the continuity of electric power for the local grid during periods when the renewable sources of energy become unavailable or insufficient.

3 The Numerical Modeling of a Diesel Generator Set

The analysis of the complex aspects of a diesel generator set requires the development of reliable numerical models that allow for simulation in different operation regimes, specifically in conditions as close as possible to the reality of the assembly internal combustion engine – the synchronous generator.

The synchronous generator represents a key component of a diesel generator set. It converts the mechanical power produced by the primary mover into electrical power. The numerical models that can be used in the study of the synchronous generator can be classified into circuit models and field models, with the ones most used in electric drive systems being the circuit models.

From the circuit models category of the synchronous machine, the most used is the orthogonal model (d-q) that allows for the study of different operation regimes of the machine, specifically the study of the assembly machine – the regulation system.

The orthogonal model (d-q) of the synchronous machine is based on the decomposition of the three-phase machine in an equivalent bi-phase one, Fig. 1. In this way the phasors system specific to the three-phase machine is decomposed along the longitudinal axis d and transversal axis q respectively.

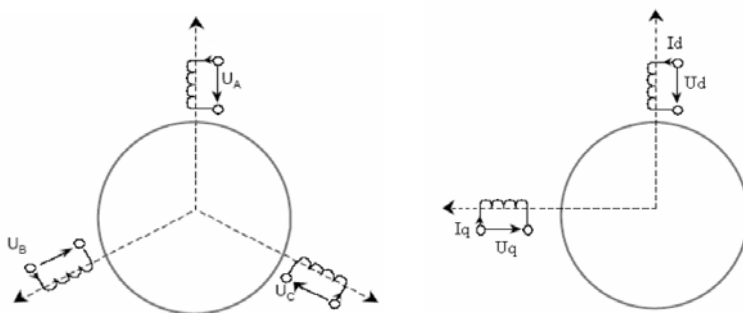


Figure 1

Transformation of a three-phase machine in an equivalent bi-phase one

The voltage equations of the synchronous generator written in a coordinate system $d_\theta - q_\theta$ situated at the electric angle θ with respect to the fixed coordinate system $d - q$ is as follows:

$$\underline{u}_{s\theta} = R_s \underline{i}_{s\theta} + \frac{d\underline{\Psi}_{s\theta}}{dt} + j\omega \underline{\Psi}_{s\theta}, \quad (1)$$

$$\underline{u}_{r\theta} = R_r \underline{i}_{r\theta} + \frac{d\underline{\Psi}_{r\theta}}{dt}, \quad (2)$$

where $\underline{u}_{s\theta}$ and $\underline{u}_{r\theta}$ are the stator and rotor voltage phasors, R_s and R_r are the stator and rotor resistances, $\underline{i}_{s\theta}$ and $\underline{i}_{r\theta}$ are the stator and rotor current phasors, $\underline{\Psi}_{s\theta}$ and $\underline{\Psi}_{r\theta}$ are the stator and rotor magnetic flux phasors and ω is the pulsation [9].

In order to study the operation of a diesel generator set either in *isolated regime* or in *emergency regime*, dedicated numerical models were developed using the Matlab/Simulink software package.

3.1 Generator Set Operating in Isolated Regime

The numerical modeling scheme used for the simulation of a diesel generator set in *isolated regime* is presented in Fig. 2, where we can distinguish: the *generator set*, the *electric load*, the normally open *switch I1*, and the *measurement* blocks.

The generator set block is composed of the diesel internal combustion engine model and the synchronous generator model, and of the voltage and speed regulation systems, Fig. 3. The main data of the simulated generator set are as follows: rated power 4.5 kVA, rated voltage 400 V, rated frequency 50 Hz.

The development of numerical models for studying the operation of the diesel generator set in continuous regime permitted us to estimate the answer of the generator in case of load variations.

In order to exemplify the effectiveness of the numerical models, we simulated the transient regime of the equipment in the case of a sudden connection of a resistive load. The initial state of the generator set is of stand-by type with no-load.

These simulation results emphasize also the capacity of voltage and speed regulation systems to keep the imposed values of generator speed and voltage.

The mechanical power (per unit) initially developed by the combustion engine is very small because the synchronous generator coupled with the engine is running without load, Fig. 4a). After suddenly connecting the resistive load, the mechanical power developed by the engine increases rapidly and after approximately 1.5 seconds, a new operation stabilized regime is reached.

During the transient regime, due to the sudden coupling of the load, the machine speed (per unit) decreases abruptly, but for a very short period of time (~0.25 seconds), after which it stabilizes at the imposed value as a result of the action of the speed regulation system, Fig. 4b).

The voltage (per unit) at the generator terminals also demonstrates a significant decrease for a short time, after which it stabilizes in less than 0.5 sec. due to the action of the voltage regulation system, Fig. 4c).

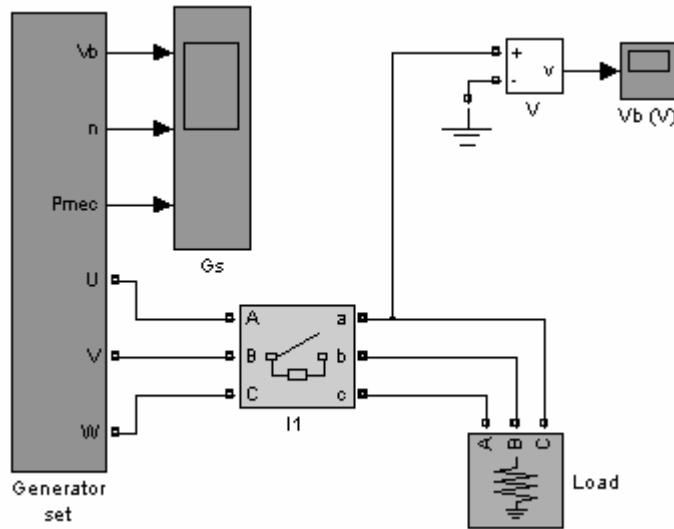
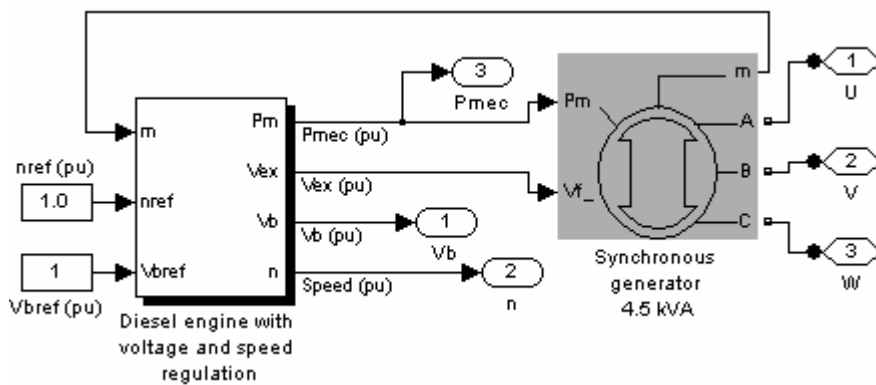
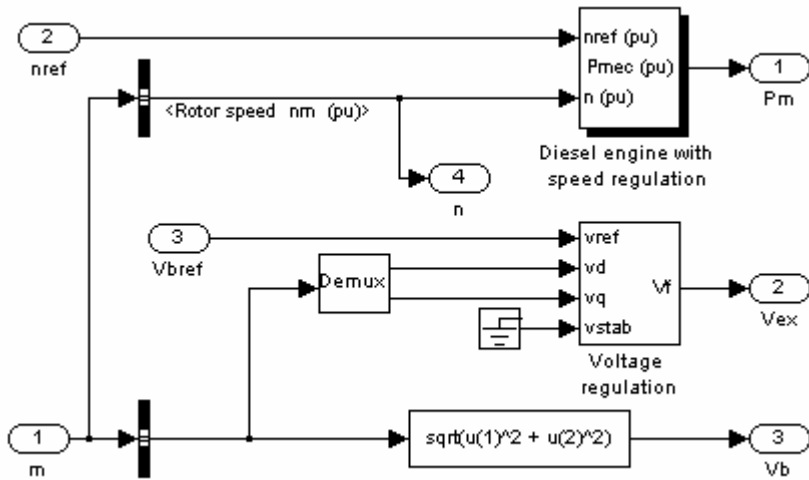


Figure 2
Simulink model of a generator set operating on a local grid



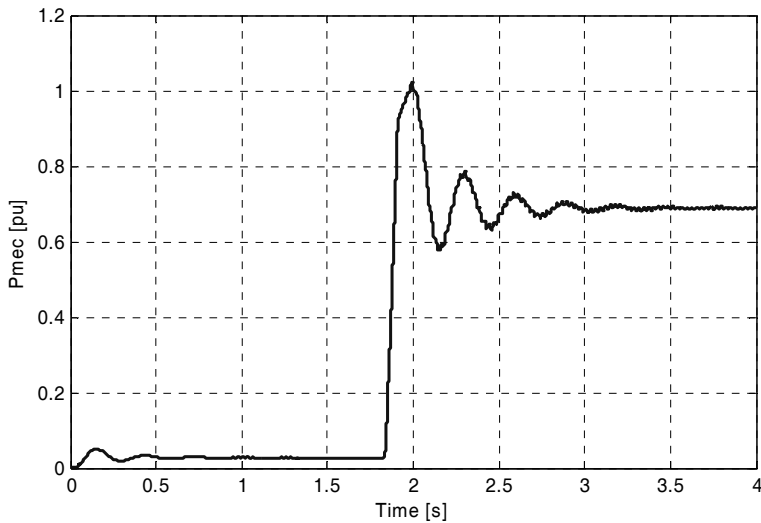
a)



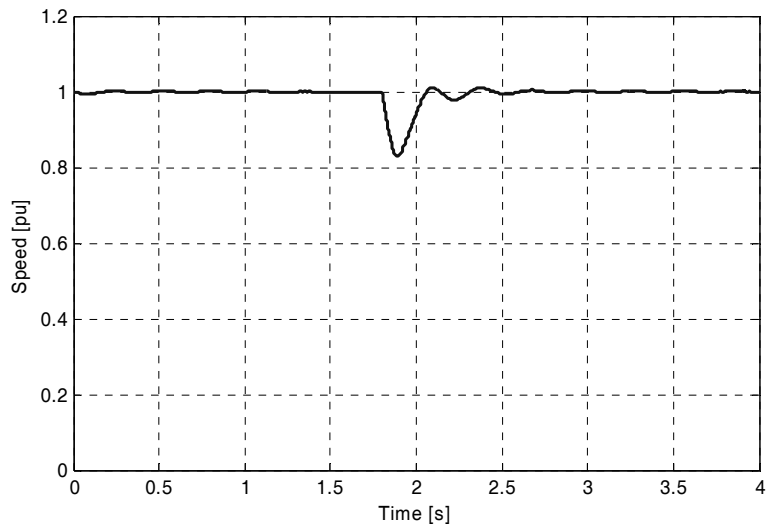
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Figure 3

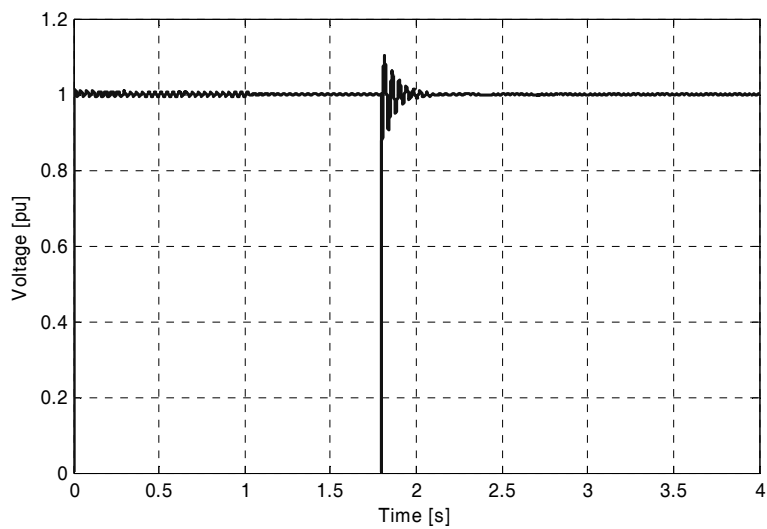
Simulink model of a generator set with voltage and speed regulation systems;
 a) global scheme of the generator set; b) Diesel engine and regulation systems



a)



b)



c)

Figure 4

Time variation of generator set quantities during the transient regime after applying a resistive load;
a) mechanical power; b) rotor speed; c) output voltage

3.2 Generator Set Operating in Emergency Regime

In the case of important equipment or objectives, electric power consumers are usually grouped into vital consumers and non-vital ones. An electric power security solution for the vital consumers is to back-up their supply by means of a diesel generator set. The installation of the diesel generator set should be done so that during a blackout resulting from a grid fault, it is possible to keep connected only the vital consumers. In the case of wind and/or solar renewable power systems, a black out could occur in the event of insufficient solar or wind power.

Such a situation is presented in Fig. 5, where we can identify the following blocks: the Grid (three-phase, 400 V, 50 Hz, which can be represented by a renewable power system), the Generator set (4.5 kVA), the Three-phase short-circuit block, vital consumers (2 kW resistive), and non-vital consumers (10 kW resistive).

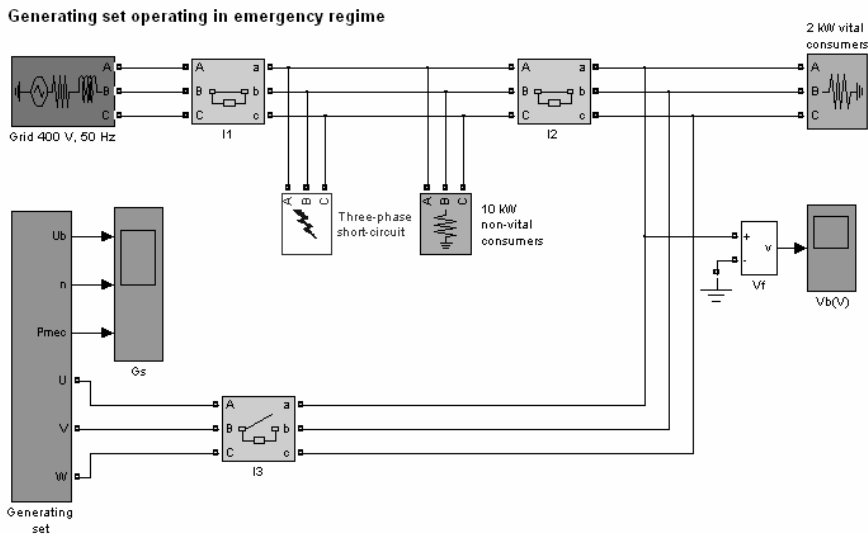


Figure 5

Generator set operating as emergency power source

The two groups of resistive type consumers have the rated powers 10 kW (non-vital consumers) and 2 kW (vital consumers), and they are supplied from the grid. When a three-phase short-circuit occurs at the grid level, the normally closed breakers I1 and I2 cut the energy supply for the non-vital consumers (10 kW), and the normally open breaker I3 connects the vital consumers (2 kW) to the diesel generator set.

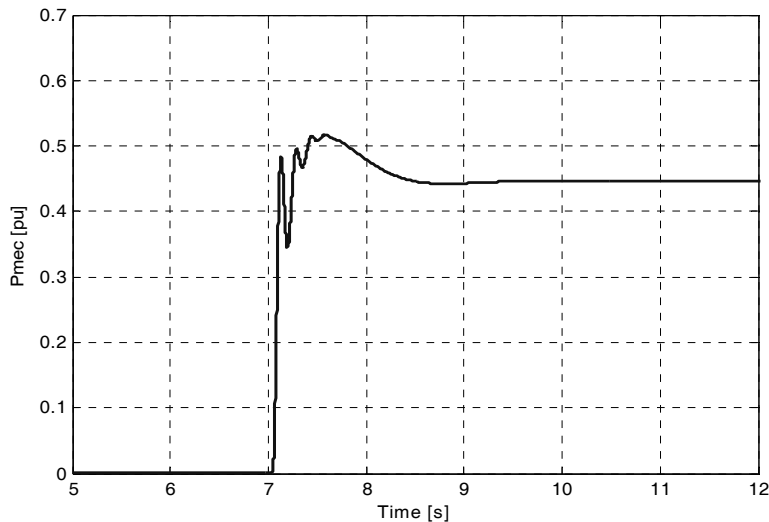
The three-phase short-circuit occurs in our case after 4 seconds from the simulation start. At time instant 4.01 seconds, the I1 and I2 breakers open, and at time instant 7.01 seconds, the I3 breaker closes in order to supply the vital

consumers. Thus the vital consumers remain unsupplied for 3 seconds, the period necessary for the diesel generator set to start-up. If the vital consumers cannot tolerate short periods of time without electricity, then the diesel generator should work in stand-by regime, being ready at any time to be connected to the load. Moreover, if the vital consumers are sensitive to voltage and frequency variations, which can occur during the commutation from the grid to the diesel generator set, a UPS system should be provided as a buffer until the extinction of the transient regime.

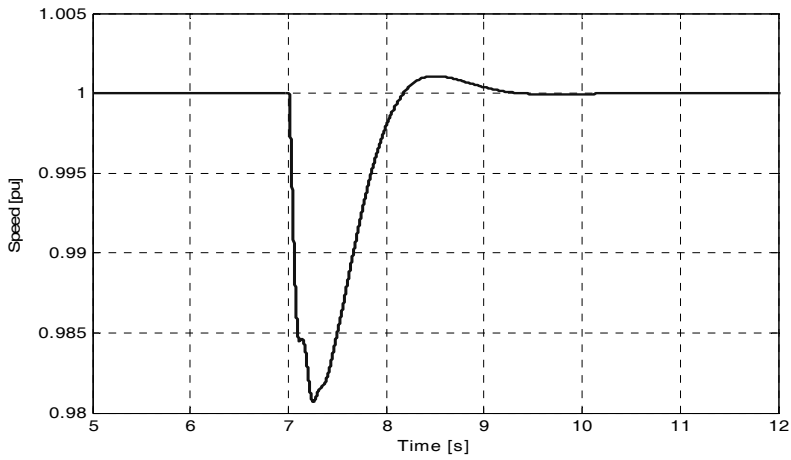
The system answer in the case of emergency is presented in Fig. 6, where we can identify the time evolutions of mechanical power, rotor speed and output voltage (per unit).

When the short-circuit occurs (after 4 seconds from the simulation start), the mechanical power produced by the generator set increases from a small value (no-load regime) and stabilizes at the value imposed by the regulation systems, Fig. 6a).

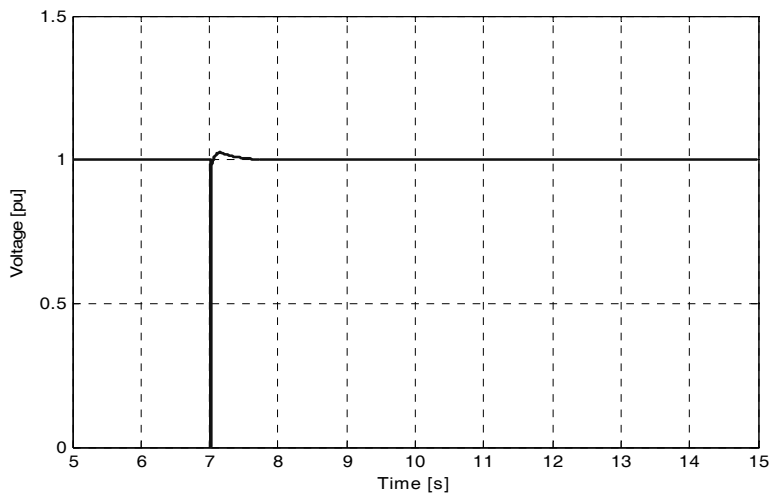
The output voltage (Fig. 6c) demonstrates an significant decrease, but for a short period of time, after which it comes back very quickly at the rated value. Such a voltage drop can be prevented by means of a properly sized UPS system.



a)



b)



c)

Figure 6

Time variation of generator set quantities when operating in emergency regime;
a) mechanical power; b) rotor speed; c) output voltage

4 Experimental Results

The goal of the experimental analysis of the paper was to register the transient phenomena after coupling a load to the diesel generator set initially operating in stand-by regime.

The diesel generator set subject to the experimental tests is a Kipor type, rated power 4.5 kVA, rated voltage 230 V, rated frequency 50 Hz, equipped with automatic start-up.

As presented in Fig. 7, the experimental set-up consists of: a diesel generator set, a laptop with a data acquisition card, conditioning circuits and transducers, load resistance, an ampere-meter, a voltmeter and an on/off breaker.

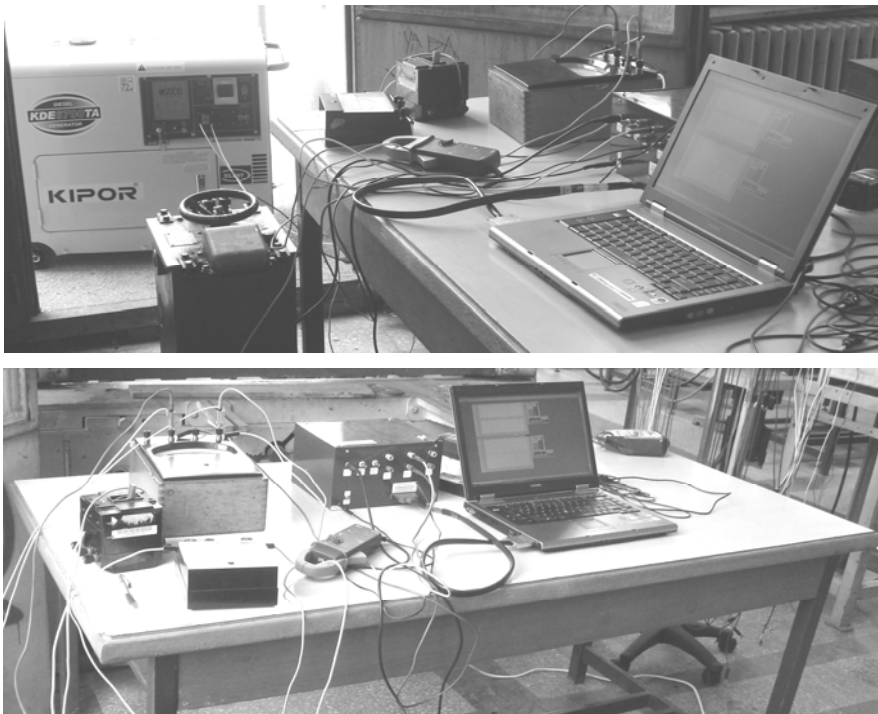


Figure 7

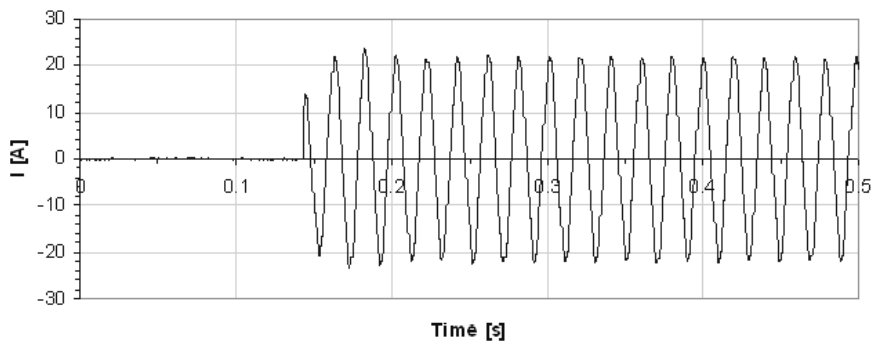
Experimental set-up used for investigations

Using a data acquisition card, we stored the time evolution of the output current and voltage produced by the generator set after applying a resistive load at the generator terminals.

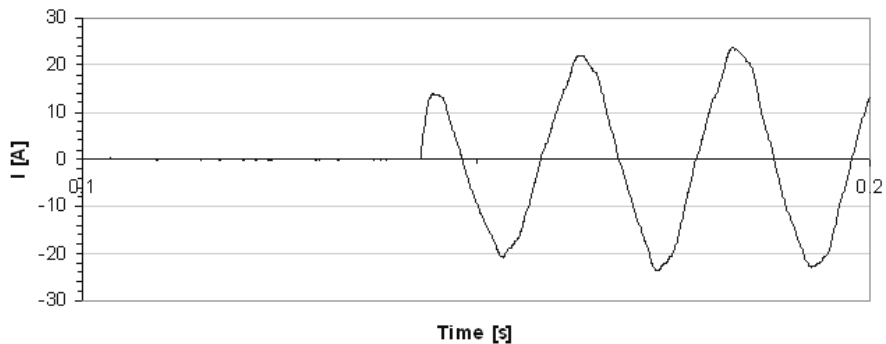
At the beginning, the diesel generator set was operating in no-load regime, the load current being null, the generated voltage 230 V and the frequency 51.6 Hz.

When operating on a local grid, the diesel generator set used for experiments is designed in such a way that starting up the machine under load condition is not recommended. Thus, after the start-up of the diesel generator set, we closed the load circuit by acting on the on/off breaker, the rms value of the absorbed current reaching 15.2 A. The power delivered to the resistive load is 3.35 kW. We can notice in Fig. 8 that the approximate duration of the transient regime is 0.13 s.

By studying the experimental results illustrated in Fig. 9, we can observe that the frequency of the voltage at the generator terminals presents a decreasing trend from 51.6 Hz in no-load operation to 51.02 Hz under load operation of 66% from the rated load of the generator (a specific trend for this type of equipment).



a)



b)

Figure 8

Time variation of load current after applying a resistive load; a) global view; b) detail

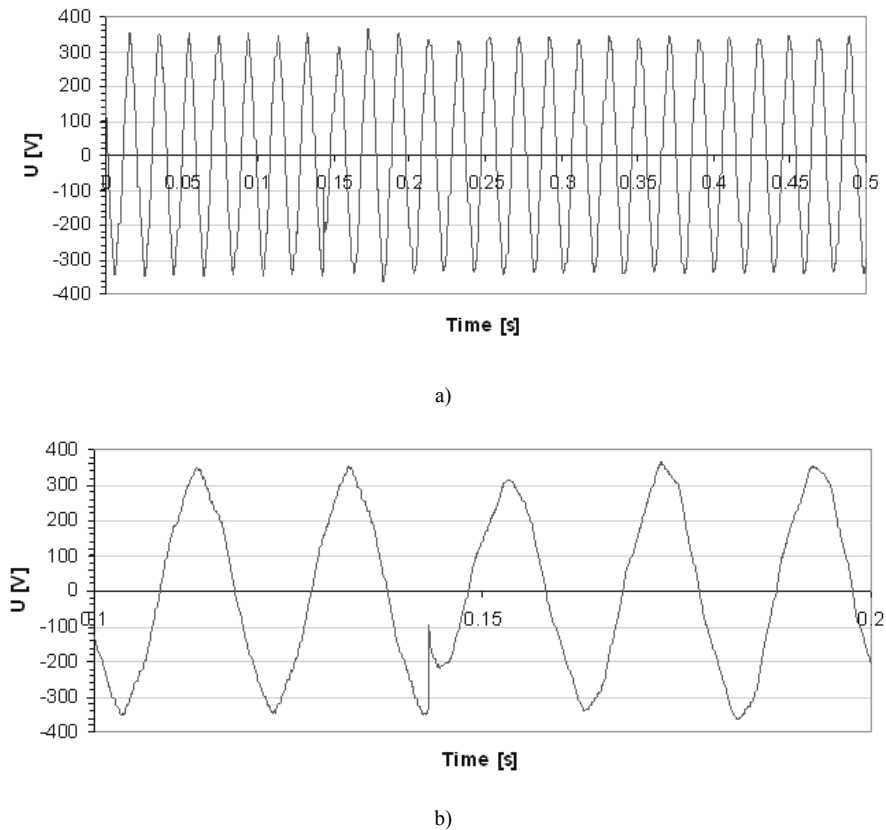


Figure 9

Time variation of voltage at generator terminals after applying a resistive load;
a) global view; b) detail

We can observe in Fig. 9 a voltage drop at the generator terminals of about 70%, but it happens for a short period of time, after which the voltage regulator brings the voltage back to the imposed value.

Conclusions

This paper deals with aspects specific to the operation of diesel generator sets working both in isolated regime and as a back-up electric energy source for vital consumers who are usually supplied from the grid or from hybrid power systems based on renewable sources.

The study of diesel generator sets was treated both via numerical modeling and experiments in laboratory.

The numerical models used for the study of the dynamic regimes of diesel generator sets were developed using a Matlab/Simulink software package. Via

numerical simulations, we determined the time variations of the main quantities useful in the study and operation of diesel generator sets (mechanical power, voltage, speed). We should observe also the usefulness, efficiency and flexibility of developed numerical models in the study of the behavior of power systems for different topologies, charge levels, load types, etc.

The experimental measurements aimed to determine the dynamic response of the diesel generator set after a sudden load connection. The diesel generator set that was experimentally tested was a Kipor 6700 one, with a rated power of 4.5 kVA.

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