ANALYSIS OF PASSIVE DIESEL GENERATOR – SUPECAPACITOR HYBRID FOR ENHANCED LOW THROTTLE OPERATION

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ABSTRACT

Diesel generator-based auxiliary power units (DG-APU) increasingly gain much attention, utilized in different civil and military applications. It is well-known that fuel economy and service life are two most important issues concerning DG-APU operation. In order to optimize fuel consumption, variable throttle position control may be adopted to keep the DG-APU in optimal operation region. Unfortunately, while the consumption is improved, system stability at light loads is sacrificed since light load operation calls for a low throttle in order to optimize fuel consumption, therefore sharp load increase may easily destabilize the system.

The situation may be improved by connecting supercapacitor bank at the DG-APU output terminals thus introducing virtual inertia which allows smoothing engine velocity response to a load step thus providing additional time to throttle controller to regulate throttle position.

Present work investigates the improvements in UC-supported DG-APU fuel efficiency and stability compared to conventional technical solutions. The research is based on mathematical modeling of the entire system, verified by experiments. The results support the presented ideas and quantitatively demonstrate the improved fuel economy and reliability of small DG-APUs.

INTRODUCTION

Diesel generators are widely used in different civil and military applications [1, 2]. Fuel economy and service life are probably the most important issues concerning their operation [3, 4, and 5]. Control in accordance with the supplied power of a throttle position, which determines fuel injection to the engine allows optimization of fuel consumption. This method is successfully used during a lot of years in various of the diesel engines [6] and diesel-generator [7] applications. For example, such approach is described in [6] implies, the regulation of a throttle position in accordance with the special map. The map defines throttle position, which provides optimal specific fuel consumption of the diesel engine. This map is obtained by multiple experiments represents curves of optimal relations between engine rpm and engine torque that provide minimum fuel supply every of a throttle position. These optimal curves are digitized in a special look-up table of the decisive algorithm for controlling microprocessor system. The system provides regulation of the throttle position in open- and closed-loop modes. It tries to set a desirable throttle place due to the needed torque and a velocity of the engine. If the closed-loop mode is applied an engine speed relatively fast achieves its optimal level that causes valid fuel efficiency. Despite the advantages, researchers point out sufficient difficulties of selecting optimal throttle position and system stability especially for light loads.

Difficulties in achieving stability of a system created as a PID regulator caused to use a predictable control based on linearized model of engine operation coupled with optimal mapping [8]. Specially developed linearized model helps to tune parameters of a regulator and to accelerate the movement of electric actuator is controlling fuel injection of a diesel. Despite the improved efficiency of engine regulation for a changeable load, applied PID regulator has a restricted range of low engine's powers where stability of operations is provided. As a result, engine velocity couldn't be diminished significantly that reduce fuel efficiency.

Researchers point out the problem with control stability of a throttle regulation as a typical. When the DG-APU, for example, is running with a light load, engine throttle position should be nearly closed in order to minimize fuel consumption. If an additional load power suddenly will be applied engine velocity may drop sharply until the complete stop since fuel injection remains on a low level. Some supplementary time needed to actuator for correcting throttle position due to this changed load. potential to shift diesel throttle lower than its maximum position. Fig. 3 includes two curves: for full throttle (FT) and 0.3*FT positions (for the sake of convenience to observe the difference between fuel consumptions) are represented in Fig.3. All other graphs for intermittent FT positions may be located between these two curves. These experiments exhibit a principal option to decrease fuel consumption by changing throttle position in accordance with the varying load. It may be fulfilled by special control system

activating throttle actuator. If this will be completed in the optimal manner fuel saving (up to 50-70%) may be achieved for a little power (less than 500W) and 5-10%% for a bigger power. The throttle control represents effective mean for the fuel supply management but decreases stability of engine functionality. The loss of stability may stop an engine since so quickly raising counteraction torque couldn't be compensated by throttle actuator because of its restricted rapidity. This situation of fuel control is absolutely undesirable and has to be prevented. The situation couldn't be improved by accelerating actuator speed because this may cause further system instability when a load will quickly decrease from high to low level. That is why the velocity of an actuator has to be restricted and the minimum throttle position should not be below some level. These circumstances determine significant inefficiencies of the existing control methods. The situation is worst especially for small diesel-generators where throttle position is usually unregulated and fixed in a position of a full load. Thus, the operation of a small diesel generator for the wide-range of power (typical for many of the diesel-generator applications) causes excessive fuel consumption, shortened service life and enlarged exhaust emission.

Nevertheless of the obvious difficulties multiple control algorithms were submitted in the past for control diesel engines by regulating throttle position [9, 10, 11]. For example, fuzzy logic control was developed in [9]. The control system based on predictive model of engine behavior was proposed in [10], sliding mode control was described in [11]. Despite of the improvements which achievable with mentioned above methods, the main problem of control stability due to the sluggish reaction of the diesel engine remains. Slow engine response produces sufficient instability of a fuel control especially at light loads. mathematical modeling may be much more effective One of the promising solutions, which significantly may change the situation, is the use of intermittent electric storage located between generator output and a load. This storage may provide a buffer, which compensates either rapidly raised or quickly failed load and this way diminishing effects of slow diesel reaction. As an intermittent electrical storage may be used ultracapacitors (UC) since having fast dynamic reply and excellent efficiency. The example of UC application for this purpose may be found in [12]. The proposed diesel generator includes variable-speed engine coupled with permanent magnet synchronous generator, which output connected to pulse width modulation (PWM) boost rectifier supplies DC link. A constant-voltage constant-frequency (CVCF) inverter on the output of DC link provides AC load feeding. In addition, UC bank is connected to the DC link by DC/DC inverter. Special electrical actuator regulates fuel injection that is being controlled in the optimal manner. Optimal control is established by the mapping of a fuel intake. Applying this system annual fuel costs and fuel consumption reduced up to 25%. In addition, proposed algorithm provides high quality of output AC voltage.

All represented above solutions of fuel control system for diesel generators control system were developed as a rule on the experimental base that impugns conclusions of competence and efficiency of the proposed methods. Applying mathematical modeling may be much more effective and useful for development of such control algorithms. A restricted implementation of mathematical approaches in the well-known works may be explained by the considerable simplification of the previously applied model that doesn't describe, for example non-linear behavior of diesel engine. As a result, these models couldn't correctly represent important parameters such as fuel consumption, transient behavior and stability, thus being problematic for suitable applications. Nevertheless, the most noticeable improvements of control systems for diesel generators with variable-speed engines might be obtained by simulation procedures on the base of the proper mathematical models.

Simulation methods for diesel engines may be found in the numerous works. Different mathematical approaches were submitted and presented in series of monographs and text-books [13, 14, and 15] as well as in the multiple scientific papers [16, 17, and 18]. Existing works as a rule are using significant simplification of applied engine model. Models represent a diesel engine as a linear or non-linear element is being determined by a transfer function. This interpretation may be useful for modeling engines operating with relatively stable speed having enlarged number of cylinders (three, four and more). However, such approach couldn't be valuable for diesel generators with one or two cylinders only.

Represented work exhibits the advantages of the UC usage in a real diesel generator with one cylinder diesel engine. Special control approach for diminishing fuel consumption was established on the model based design. Developed mathematical model was founded and verified by multiple experiments with a real diesel generator. Control algorithm provides stable and qualitative operation of diesel generator for different load variations were investigated and evaluated.

The paper consists of three main parts. Preliminary results of diesel generator tests and main concepts of fuel consumption control are presented in the first part. The methodology of diesel generator modeling and its verification with simulation outcomes are drawn in the second part. Investigation of numerous control algorithms for fuel supply is given in the last part of the paper.

PRELIMINARY RESULTS OF DIESEL GENERATOR TESTS AND MAIN APPROACHES OF FUEL SUPPLY CONTROL

The object of the present investigation was diesel generator model Yanmar L48AE. It consists of single-cylinder, vertical 4-cycle air-cooled diesel 3.5kW, 3600 rpm, synchronous generator (2.5 kW), full bridge six diodes rectifier and control system forregulating output voltage keeping it on the constant 28 V DC level. Stand-up for testing diesel generator is shown in Fig.1. Diesel generator L48AE [19] has typical output characteristics are depicted in the Fig.2. Fuel consumption for the full-throttle position has a minimum level close to the 250 g/kWh in the range of 2700-2800 rpm of engine speed. Manufacturer suggests working with the full throttle position and maximum speed in spite of an opportunity to decrease sometimes fuel injection. Hereby prefer sacrificing of fuel supply reduction to the stability of generator functionality. However, fulfilled experiments (Fig.3) showed

The main idea of this work is to connect a UC on the generator output. UC will diminish during a transient period a current (and therefore, a counteraction torque) when a rapid load is applied to the generator. This way, an additional time for

a correction of fuel injection will be provided to the throttle actuator that will improve control stability.

The principle framework of a control system for fuel supply management is shown in Fig.4. It includes electronic regulator for output voltage stabilization, a throttle actuator with control system, special sensors for providing information regarding output current, voltage, power and a bank of UC is connected directly to the DC output. The direct connection of UC to the generator was chosen due to the relatively small generator voltage (28V DC). Direct connection prevents the use of an additional DC/DC converter and low voltage permits applying relatively small number of UC for the bank.

Development of the control system for throttle control was done by the model based design. Considerations and a methodology which were applied for creating mathematical model are presented in the follow section.

Fig.1: Experimental set-up for testing diesel generator Yanmar L48AE.

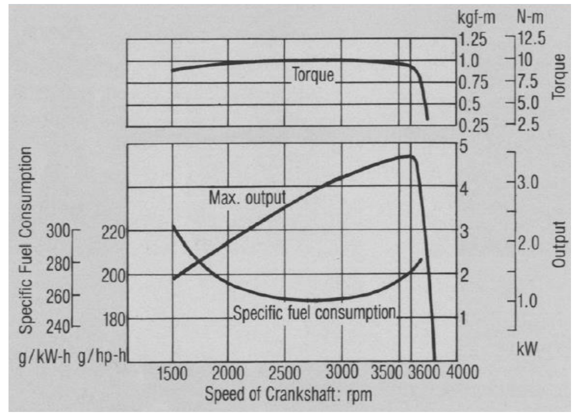


Fig.2: Typical output curves diesel generator Yanmar L48AE.

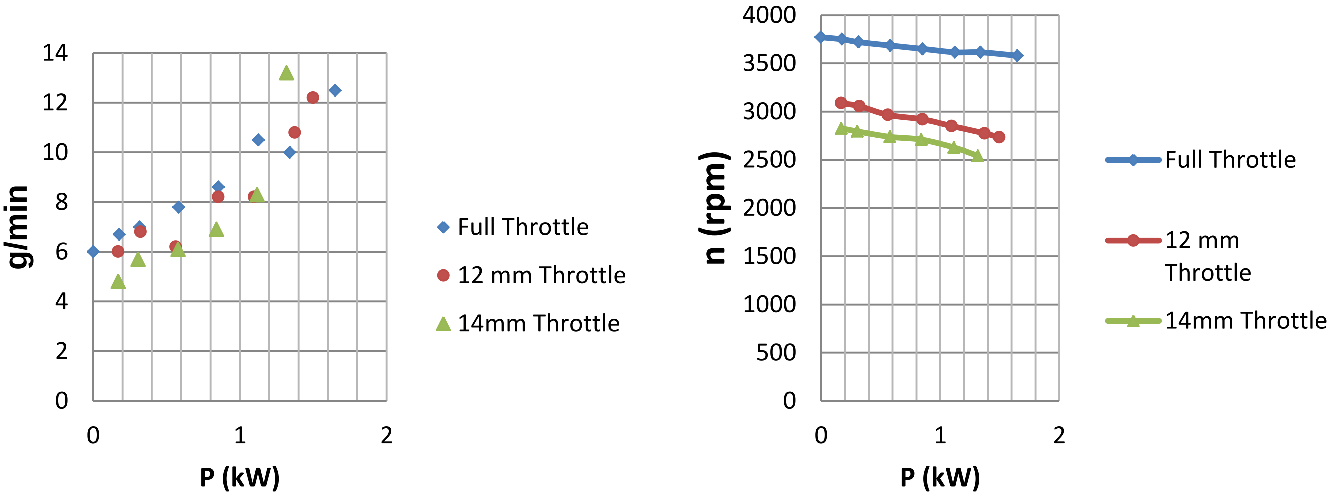


Fig.3: Experimental results of fuel consumption and rotation velocity for different throttle positions.

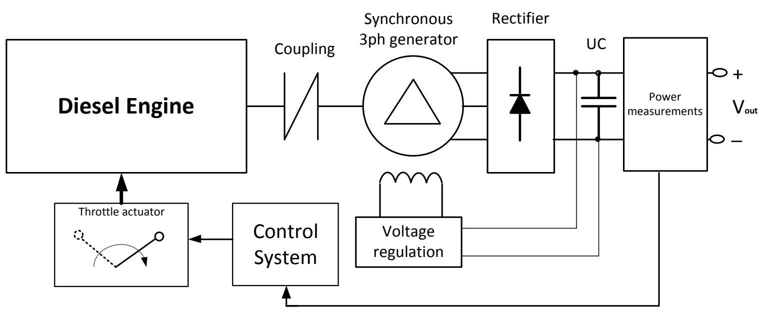


Fig.4: Diesel generator with the system of throttle position control.

METODOLOGY OF SIMULATION

Verification of real diesel engine parameters

Some experiments for measuring important characteristics and parameters of diesel generator previously to model development were carried out. These measurements assisted to verify adequateness of the model to a real diesel generator. Firstly, the AC voltage form of the synchronous generator output before the rectifier was recorded by the LeCroy oscilloscope (Fig.5). The rotating crank velocity was estimated based on these obtained data and results were shown in the Fig.6. The velocity was calculated as an inverse value to the duration of half-period of AC voltage.

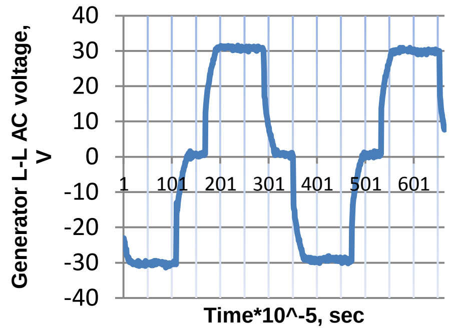
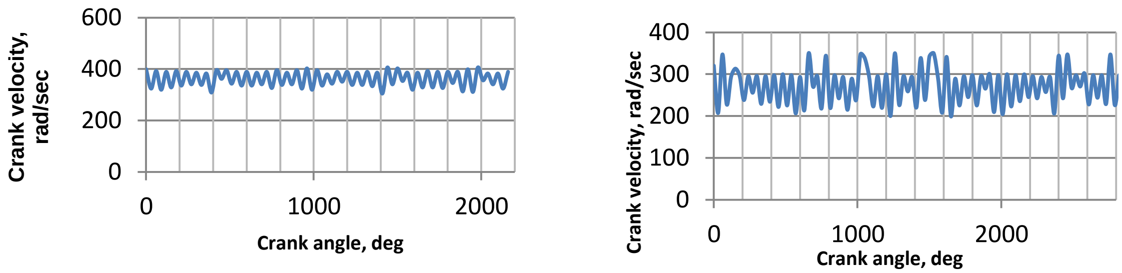


Fig.5: A sample of AC Line-to-Line voltage before a rectifier



a) b)

Fig.6: Changing of crank velocity versus angle of crank rotation: a) Full Throttle (FT), 0A current; b) 30% of FT, 20A current.

The following observations regarding crank velocity deviations can be obtained: 1) the velocity alterations grow up with the increasing of a load and when throttle located near its lowest position; 2) velocity's deviations vary from ~20% to ~30% of the average level.

The additional experiments were done for determination of diesel engine velocity change versus load current for different throttle positions (Fig.7).

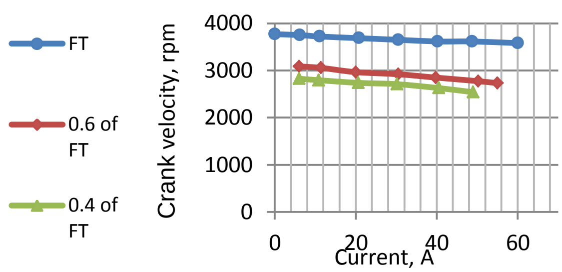


Fig.7: Crank velocity drop versus increasing load current for different throttle positions

Model development

Simulations of diesel engine, synchronous generator and a load were created and connected together for the entire model. Simulation of diesel engine was developed based on the representation of the forces (torque moments) are changing due to the crank angle. Typical diagram of torques versus crank angles was developed for every of engine cycles (intake, pressing, expansion and exhaust) (Fig.8). The special procedure, which calculates the actual torques based on the current crank velocity and throttle position permits evaluation of existing output engine and generator velocities. The assessment of fuel supply was fulfilled in every of simulation running. This was done by integration of the output generator power and summation of fuel injected in every engine cycle.

The standard model of synchronous generator from Simscape library of Simulink was applied here. The function of generator EMF was established by experimental tests for different values of excitation currents and generator rotating speed. The normalized curve of EMF was used for the simulation of a real EMF.

Electronic regulator of generator voltage simulates control process of excitation current and was created from the components of the standard Simulink library. Additional electrical/electronic components are needed for model completing were chosen from this library as well.

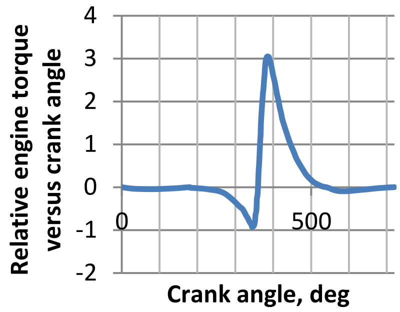


Fig.8: Engine torque produced during rotating crank angle

INVESTIGATION OF DIFFERENT CONTROL ALGORITHMS FOR CONTROL THROTTLE POSITION.

Three main approaches for throttle position control were investigated. They are: 1) Constant value of FT, which was applied as a basic management strategy for comparison; 2) Look-up table; 3) Original algorithm of throttle control based on output voltage feedback with asymmetric cycle of throttle speed.

Look-up table algorithm was investigated previously since the algorithm with constant FT is typical and its parameters are provided by manufacturer.

Look-up table algorithm based on previously determined mathematical relation, which provides an optimal throttle position as a function of some important output parameters, preferable output generator or load power. The function was found empirically and connects generator output DC power with desired throttle position. The mathematical expression for this generator is:

$$ThrotPos=0.7+P_G/6000 \quad , (1)$$

The third control algorithm called asymmetric cycle throttle regulation (ACTR) is represented in the diagram Fig.9. It includes block of output voltage set point "Minimal Voltage level", which determines the desired output voltage; input of actual measured output voltage "Current Voltage"; error element with hysteresis characteristic; switching element with two signal inputs and one controlling input; two additional set points for establishing an actuator speed during closing and opening throttle valve and an integrator element. The difference between actuator speeds "down" and "up" is important since it determines the stability and total fuel efficiency of the control algorithm. The setting of "Minimal voltage level" defines fuel consumption as well and this level has to be slightly lower than that of desired generator output. The presence of UC on the output terminals gives additional time for the correction of the throttle position. The time constant of UC-load circuit is desirable to be approximately equal to the time needed for the actuator to cover quarter to third of the full throttles distance. The correct selection of UC provides desired precision of generator voltage. The higher is UC capacitance the better is voltage constancy. At the same time the oversizing of UC causes the loss of engine stability and even its halting. Unacceptably large UC keeps output voltage prolonged time and actuator plenty to drive the throttle to the lowest position. On the following step of loading increase actuator isn't able to open a throttle and an engine will stop.

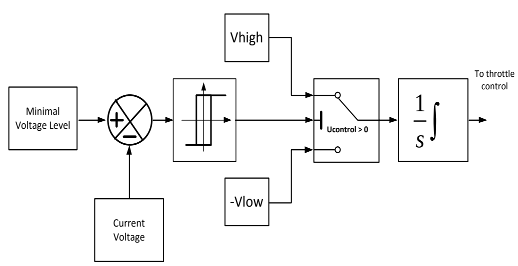


Fig.9: Principle block-diagram of ACTR control

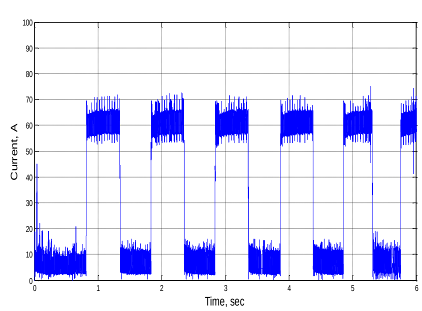


Fig.10: Diagram of current regulation during experimental simulations.

Every of the mentioned above control principles were applied with- and without UC. The pulsed load diagram was chosen with duty cycle 50%, period 2 sec and two resistances - 4Ω and 0.5Ω that determine high and low levels of a load. The periodically changing load with relatively significant difference between low and high current levels was selected for deep examination of the submitted control strategies regarding their stability and voltage regulation. Fig.10 shows diagram of current regulations during simulation procedures. The output generator power is changing in accordance with the current since output voltage remains near constant. Multiple runs of simulation procedure were fulfilled for verification the major system parameters such as system stability, voltage regulation and fuel efficiency. The results are shown in the Table 1. Below these algorithms are represented by different graphs are describing dynamic behaviors of control systems are created due to these control strategies.

Fig.11 represents throttle control due to the Look-up-table strategy. The curve of throttle position is changing in conformity with the output power as follows control algorithm (1). Nevertheless, throttle lags behind the real supply power because of its restricted velocity of location changing. The position of a throttle is shifting between 0.7FT and FT. This relatively narrow range is determined due to the selected throttle velocity that has to provide sufficient engine stability and output voltage regulation. Results of this algorithm: output voltage deviation is close to 2-3 V, fuel consumption ~2.8 kWh/kg (without UC) and ~3.0 kWh/kg (with UC).

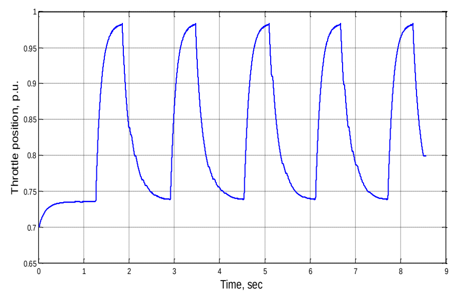
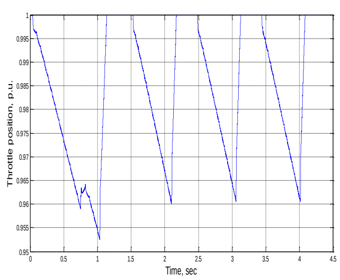


Fig.11: Throttle control due to Look-up-table algorithm

The succeeding control algorithm for investigation was ACTR. It is characterized by two actuator velocities. The first of them is called as ”velocity down”. It has negative value and determines the speed of the throttle closing. The second -”velocity up” (has accordingly positive value) defines the speed of the throttle opening. The velocity unit is equal to the relative portion of FT position changes during the time and has common denotation – throttle portion per sec (TP/sec). Two alternatives of velocities (-0.1/1 TP/sec and -0.3/1 TP/sec) were investigated. Fig. 12 and 13 represent throttle control for (-0.1/1 TP/sec) without UC and for -0.3/1 TP/sec with UC correspondingly. Graphs of these (Fig.12, 13) show that the absence of UC causes the need to reduce throttle velocity “down”, otherwise a stability of control may be insufficient. In turns, the enhancement of velocity “down” permits increasing of throttle range during control process and the fuel efficiency as well.



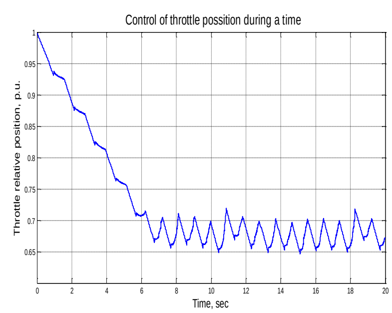


Fig.12: TC for ACTR without UC for -0.1/1 TP/sec

Fig.13 TC for ACTR with UC for the -0.3/1 PT/sec.

Positive improvements after UC applying to the control system may be distinguished from these graphs: the deepness of throttle control is higher with UC i.e. fuel consumption has to be better (see Table 1). In both cases the stability of output voltage for ACTR may be demonstrated by the graph Fig.14.

The output voltage remains very close to the set-point value and a maximum voltage deviation for the entire current range doesn’t exceed 1.5-2%.

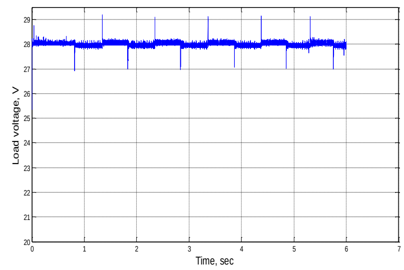


Fig.14: Output voltage deviations during ACTR

One of the criteria for verification of model correctness may serve graph of crank/generator rotation velocity depicted in Fig.15. Graph in the Fig.15 represents crank rotation speed of the diesel engine immediately after the beginning of a starting process and during some period of time following it. Engine speed are provided at the beginning by the starter motor is being raised, after switch "off" of the starter it decreases and shortly returns to the nominal value. Curve of engine velocity shows some diminishing of average speed after an applying of additional generator power (current) that accurately matches real experimental data.

Engine functionality is characterized by significant sweep of a momentary crank speed. The reason for this lies in the fact that four stroke diesel engine of a generator has a single cylinder and a rotating force (torque) is applied periodically and relatively short period of time only. The variability of an engine instantaneous velocity can be traced by the change in the output voltage is exactly repeating the velocity of crankshaft (See Fig.6 (a,b)). This circumstance determines the principal stability problems of the throttle control. The main method for improving control stability is the decreasing of the range for throttle movement and limiting its velocity that adversely affects the fuel efficiency. In spite of this, every of submitted algorithms have its own range of throttle velocities and, thus, its own standards of engine fuel consumption. The submitted ACTR with utilizing UC on the generator DC output shows the best results between all considered control strategies and may be suggested for the implementation in such diesel generators.

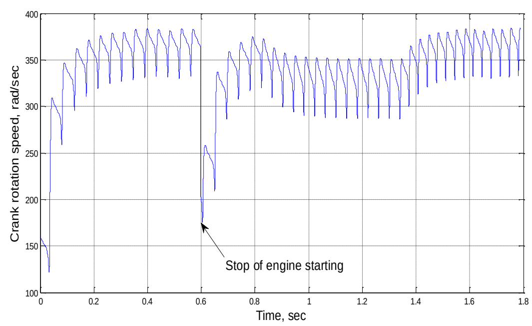


Fig.15: Crank (generator) rotating velocity during the time

Table. 1. Fuel consumptions different algorithms of throttle position control

Fuel consumption, kWh/kg			
Full throttle (without regulating)		without UC	C=5F, r=0.02Ω
		2.8	3.0
Look-up-Table		3.9	4.0
Asymmetric control of throttle speed	-0.1/1	2.9	4.8
	-0.3/1	2.9	4.9

RESULTS AND CONCLUSIONS

1. Throttle control represents significant method for improving fuel consumption and reliability of diesel generator. Nevertheless, this control is risky especially for small one-cylinder engine in terms of control sustainability. Fast load ramps may very easily cause to engine instability and even to it's halting that absolutely inappropriate in real practice.
2. The usage of UC on the generator DC output may provide sufficient improvement of engine operation sustainability; however it should be applied together with the appropriate control algorithm considerably enhances engine efficiency.

3. Special mathematical model of diesel generator with one cylinder engine was developed by the means of Simulink (MATLAB) software and later was verified by comparison between modeled and experimental data on the real diesel generator Yanmar L48AE.
4. The model of diesel provides flexible and accurate simulation of engine dynamic behavior since it calculates engine torque separately for every of four strokes: intake, compression, combustion and exhaust. More of this, representation of engine torque for every stroke separately permits accurate estimation of fuel consumption.
5. A model of synchronous generator and additional electrical/electronic elements was provided by the standard components of Simulink and toolbox Simscape.
6. Developed simulating model was applied for investigation different control algorithms. Assessments of control sustainability, parameters of output voltage, current, power and fuel consumption were fulfilled for the special testing loading algorithm with pulsed load power.
7. It was found that the UC usage together with the ACTR provides the best results for fuel consumption, system stability and output voltage regulation. This approach achieves significant diesel generator stability, improvement of fuel supply by 60-63% compare to the recommended regime (constant FT) and output voltage constancy ±0.1-0.2 V from the nominal level.

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