Speed control with incremental algorithm of minimum fuel consumption tracking for variable speed diesel generator

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Abstract

This paper presents a model of a diesel-combustion-engine-based variable speed generation unit driving a permanent magnet generator loaded by a power converter. Variable speed operation of the internal combustion engine facilitates fuel saving when the load profile changes, but it requires a power conditioning unit such as an electronic converter. Power converter operation is well known from wind energy conversion systems, in which variable speed operation increases their efficiency. The paper presents modeling and speed control of an exemplary diesel engine, and control of output voltage and current of the power electronic converter loading the generator. Special attention has been paid to elaboration of the methods of minimum specific fuel consumption points tracking for the given load. Incremental algorithms can find minimum specific fuel consumption in the case in which the details of fuel consumption curves are not exactly known. The incremental algorithm has been adopted from wind energy conversion systems and partly modified to avoid torque peaks during incremental step changes of reference speed. The concept has been validated in a simulation using data of a real model of an internal combustion engine through a two-dimensional approximation of fuel consumption characteristics.

Keywords: diesel generator, power electronics, speed control, minimum specific fuel consumption

1. Introduction

Energy conversion systems driven by internal combustion engines are widely used as emergency power supply systems during mains outage, and as primary energy sources in remote areas [1]. In the second case, the systems operate continuously, and energy conversion efficiency is an important issue, not only due to fuel price, but also due to possible logistic problems with fuel distribution. To decrease fuel consumption, diesel-engines-based power generation units are supported by wind turbines and together they comprise so-called hybrid wind-diesel power systems [2]-[4]. Simultaneously, diesel engines assure reliability in power production at poor wind speed conditions. A recent study includes also cooperation with other energy sources like photovoltaic (PV) sources, as well as with energy storage systems connected in a micro-grid [5][6]. However, it is not possible to exactly match instantaneous wind power, PV power, and the load profile to assure the best operating point of the fixed speed diesel generating set. Thus, to obtain the most optimized operation of micro-grid, energy management methods are developed. It is especially important in isolated micro-grids, in which the load power profile varies, and energy management should take into consideration not only variability of power production from renewable energy sources, but also variability of load power. Additional issues are related to the transient state of diesel generator starting-up. Slow dynamics of diesel generator during starting-up require fast short-term energy storage systems like super-capacitors, and adequate energy management [7].

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Moreover, a multi-objective optimization process of the whole power system must be conducted to select adequately the required power of renewable energy sources, energy storage system and diesel generator for assumed variability and range of load profile [8][9]. Integration of renewable energy sources, energy storage systems and diesel generators can be made in different ways, i.e., with the use of AC grid [10], DC grid [8] or in mixed manners.

However, rarely is variable speed operation of the diesel generator taken into consideration, especially when the AC micro-grid is proposed as the interface for system components coupling. Usually, in the AC micro-grid case, the diesel generator drives a classic synchronous generator operating with constant speed to keep constant frequency on the generator terminals. The concept of variable speed operation can increase conversion efficiency by matching rotational speed to the actual demanded power. Variable speed operation of the internal combustion engine, like variable speed wind turbines, requires a dedicated power electronics converter, and appropriate control of power converter and combustion engine depending on the demanded power.

The concept of a variable speed generator was proposed in the late 1990s, but initially, the properties of internal combustion engines were not analyzed. Instead, papers focused on energy quality [11][12] by introduction of controlled power converters with an output LC filter (so-called sinusoidal voltage inverters). Later, deeper studies on holistic properties of variable speed diesel generation sets were published, taking into consideration the super-capacitor bank [13], battery [14] or renewable energy sources integrated in a micro-grid. A general scheme of the analyzed variable speed internal-combustion-engine-based generation unit equipped with a power electronics converter is shown in Fig.1.

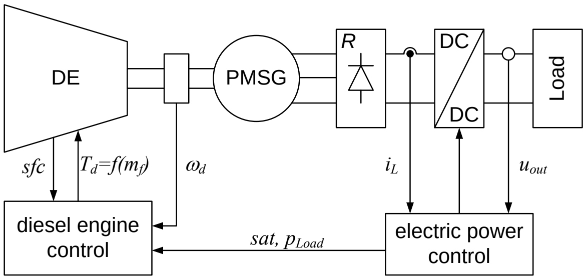

Fig. 1. General scheme of an internal-combustion-engine-based generation unit with a power converter.

The key role of a DC/DC electronics converter responsible for direct loading of the permanent magnet synchronous generator PMSG is control of the generator current responsible for loading torque, and intermediate DC voltage. A single phase or three phase DC/AC converter is responsible for standardization of the output voltage amplitude and frequency (e.g. 230V, 50Hz). An intermediate DC bus converter decouples two electronic systems and makes it possible to keep the generator frequency different than the grid/load AC voltage. The power electronic system plays another important role, which is current limitation during the load side short circuit. However, this issue is beyond the scope of this paper.

Different topologies of power converters are possible depending on the power and type of an AC interface (three phase or single phase) similarly to wind energy conversion systems technologies. For low power units, a machine side cost effective converter can be composed of a cascade-connected three phase six pulse diode rectifier and a DC/DC boost converter. This solution can be cheaper than a three phase full bridge rectifier, and does not require an additional rotor position sensor (encoder) usually used in vector control of full bridge active converters operating with synchronous machines. From the point of view of speed control of the diesel generator, the topology of machine side converters does not matter, due to the fact that the speed control loop is much slower than possible current and torque ripples of the generator.

A variable speed generation unit can operate as a standalone power system, a grid connected system, or parallel to other sources in so-called micro-grids - both types, DC and AC. The DC/AC converter acts as a load for the rectifier and the topology of the DC/AC converter does not influence torque pulsations directly, because the instantaneous generator current is controlled by the DC/DC converter independently of the DC/AC converter. Only the active power (average value of instantaneous power) taken by the DC/AC converter is important from the mechanical loading torque viewpoint, because it determines the average value of rectifier current, so the generator torque, at a given engine speed. From this point of view, the DC/AC converter can be replaced by load with resistive nature, representing some general power consumed by the load. The generator current (so the loading torque) is controlled entirely by the boost converter, and only this part of the power electronic conversion system is taken into consideration, like in [15].

A novel contribution of this paper is elaboration of the incremental algorithm designed to find the minimum specific fuel consumption point, which has not been found in the literature in any version dedicated to internal combustion engines. Additionally, implementation of the algorithm in a computer model built with the use of approximated characteristics of specific fuel consumption, and computer verification at different load conditions is an original contribution of the paper. Improvement of the speed control loop by adding the loading torque information to the output signal of the engine speed controller can also be treated as an original contribution.

2. Diesel engine model and speed control loop

Engine speed is controlled with an electronic actuator responsible for fuel injection, and its control signal responsible for injecting mass of fuel m_f influences on the driving torque T_d. Specific fuel consumption *sfc* is obtained from the governor electronic system, and actual speed ω_d is calculated with a tooth wheel sensor. The block responsible for engine speed control consists of a speed controller, incremental algorithm of minimum specific fuel consumption point tracking, and the part indentifying load power to improve the dynamics of engine speed control.

The speed controller of a diesel engine is similar for constant speed and variable speed operation, and the parameters of the controller depend on the maximum torque, moment of inertia and delay of the governor. A model of the speed control loop is shown in Fig. 2, in which T_{Load} is loading torque, T_f is friction torque, J is the total moment of inertia, and m_f is the fuel mass needed to create the engine torque T_d. The reference speed is usually matched to the actual loading power in relation to the minimum fuel consumption for the given load [15][16]. The characteristic is usually provided by the manufacturer (so-called optimal speed characteristic), but it can be determined also in laboratory tests. However, the optimal speed characteristic is valid for specific conditions and may vary depending on fuel mixture, altitude of installation, ambient air pressure (density), temperature, and due to ageing of engine components.

Time constant τ_2 of the actuator depends strongly on the type of fuel injection. For direct fuel injection, the actuator's time constant is small, in the range of single tens milliseconds, whereas for indirectly injected fuel, the time constant can be in the range from 0.1s for small engines to 0.5s for high power engines. In this paper, the analyzed diesel engine Kubota V1505 is small and it is equipped with indirect fuel injection. Due to unknown parameters of the actuator, time constant τ_2 has been set to 0.2s.

The delay time τ_1 of the diesel engine can be calculated with (1) [17].

$$\tau_1 = \frac{60 S_T}{2Nn} + \frac{60}{4N} \tag{1}$$

where S_T – number of strokes, N – engine speed in rpm, n – number of cylinders. For analysed four strokes, four cylinders engine, the delay at 1500rpm equals τ_1=0.02s, and for 3000rpm it equals τ_1=0.01s, that is one order smaller than the assumed time constant of actuator τ_2.

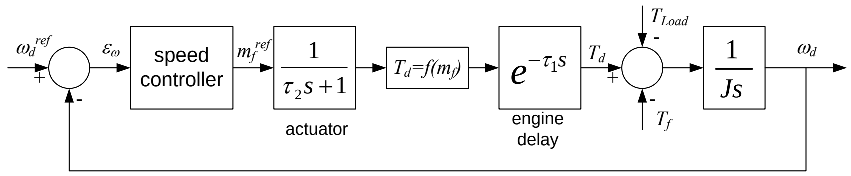

Fig. 2. Model of classic speed control loop of a diesel engine.

The classic control method shown in Fig. 2 has a relatively slow response to both change of the loading torque T_{Load}, and change of the reference speed, especially in indirectly fuel injected engines. In a variable speed diesel engine the speed change is provoked by the change of loading power P_{Load}. In control theory, loading torque T_{Load} can be treated as a disturbance; when we know the value of loading torque T_{Load} and the $T_d=f(m_f)$ function, a significant improvement of speed control loop can be proposed, by introduction of so-called disturbance rejection. Loading torque T_{Load}^{calc} for disturbance rejection loop is calculated with (2),

$$T_{Load}^{calc} = k_T i_L^{ref} \tag{2}$$

where k_T as torque factor shows the relation between the converter current (generator current) and electromagnetic torque of the machine. This factor is almost constant in the range of nominal torque. Depending on the model, the speed controller gives the output signal responsible for the mass of fuel required to deliver the wanted torque of the engine. Function $T_d=f(m_f)$ is slightly nonlinear and a detailed description can be found in [18]. Fortunately, the function is monotonic and an inverse function can be found to calculate the required amount of fuel to compensate for the loading torque, which can be used to create the disturbance rejection loop as it is shown in Fig. 3a.

Direct $T_d=f(m_f)$ and inverse function of $f^{-1}(m_f)$ can be removed from the model, and then, the speed controller will be directly responsible for the part of torque compensating for reference speed changes (dynamic torque), friction torque T_f, and any inaccuracies in determination of loading torque T_{Load}^{calc} and $T_d=f(m_f)$ function. The simplified model and speed control loop are shown in Fig. 3b. It has to be clearly noted that the proposed simplification is made only for modelling purposes. In practice we need to find an inverse torque fit function and use it in the disturbance rejection loop, or in series to the actuator transfer function to make speed control loop linearization. There may occur some inaccuracy in the determination of parameters of nonlinear, monotonic torque fit function. Moreover, the function may slightly vary during engine exploitation, like the *sfc* function. This may cause that the disturbance rejection loop will provide a higher or lower signal than actually responsible for disturbance rejection. However, this is a minor drawback, because the closed loop system of speed control will compensate for this inaccuracy.

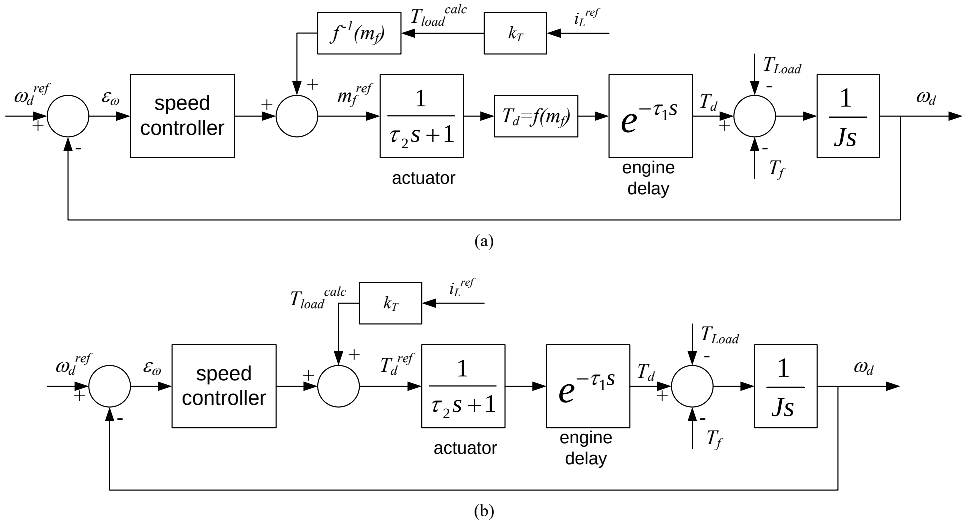

Fig. 3. Models of the speed control loop of a diesel engine with disturbance rejection, a) with torque fit function $T_d=f(m_f)$, and b) simplified.

A comparison of the classic speed control model and the simplified one with disturbance rejection is shown in Fig. 4. Fig. 4a presents the case of response to disturbance change (step change of loading power, so at constant speed it changes the loading torque) at a constant reference speed. Fig. 4b presents the response of a diesel engine to step change of reference speed at constant loading power. Such a situation does not exist in practice in a variable speed generator, because speed is referenced depending on load change, but it gives information about control loop properties (response to the reference speed change at constant load power). In this case, the constant loading power will change the loading torque when the speed changes, but it does not make sense to show speed changes at constant torque. For constant disturbance, both methods are similar, because in the classic method the speed controller will compensate for the disturbance influence and when this disturbance is unchanged, this part of control signal will not be changed. Optimal speed tracking, depending on load power changes, will be shown in the next sections. Simulation tests were conducted for the parameters shown in Table 1.

Table 1. Parameters of the mechanical system for simulation tests

Parameter	Symbol	Value
Engine moment of inertia	J_d	0.01726 kgm^2
Flywheel moment of inertia (SAE 6.5’’)	J_f	0.1775 kgm^2
Generator moment of inertia (EMRAX 228)	J_g	0.0421 kgm^2
Max. engine torque	T_{d_max}	100 Nm
Delay time constant	τ_2	0.02s
Actuator time constant	τ_1	0.2s
PI speed controller time constant	T_i	1s
PI speed controller gain	K_p	1

It can be seen in Fig. 4 that introduction of a disturbance rejection structure improves engine responses to reference speed change or loading torque change even if the loading torque signal T_{Load}^{calc} is calculated with an error. 15% error in the loading torque assignment was taken into consideration. It can originate from the torque fit function m_f coefficients inaccuracy, neglect of the friction factor, or imperfect knowledge on the torque factor k_T of the electric generator.

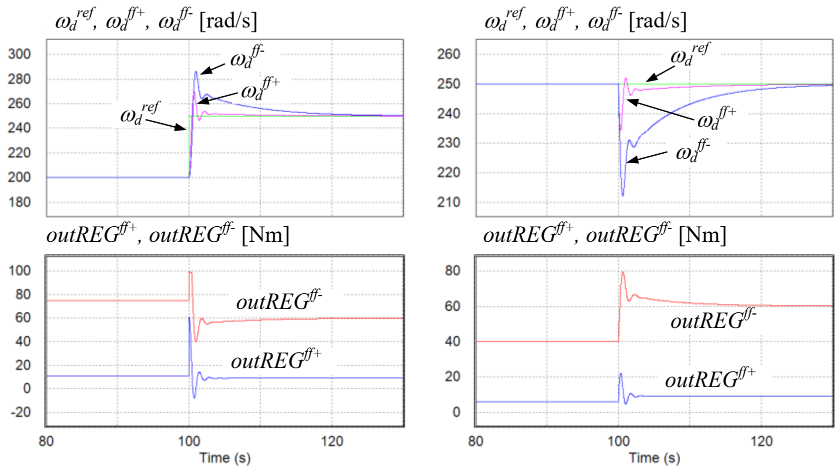

Fig. 4. Responses of the diesel engine for classic speed control and when equipped with disturbance rejection to a) step change of reference speed at constant loading power, and b) step change of the loading torque (ω_d^{ref} – engine reference speed, ω_d^{ff+} – engine speed response with loading torque feed-forward structure, ω_d^{ff-} – engine speed response without loading torque feed-forward structure, $outREG^{ff+}$ – speed controller output signal with loading torque feed-forward, $outREG^{ff-}$ – speed controller output signal without loading torque feed-forward).

3. Specific fuel consumption characteristics

The basic characteristics of an exemplary diesel engine KUBOTA V1505 are shown in Fig. 5. The engine has an optimal area of operation points for around 80% of rated torque and for the speed range covering fixed speed 157rad/s and 188rad/s (for 50Hz and 60Hz AC voltage respectively, produced by a four poles classic wound rotor synchronous generator at fixed speed). The maximum power which can be produced by the engine at 157 rad/s (50Hz voltage) equals 15kW, and this is 60% of the maximum power of the engine (25kW) delivered at 290rad/s. The same power lower than the maximum can be produced at a different speed, but it requires a power electronic conversion system. This way the frequency of the generator related to the mechanical speed may be different than 50Hz, and the converter is responsible for standardization of the output AC voltage parameters.

Speed regulation can be made according to the characteristic of minimum specific fuel consumption depending on the engine power provided by the manufacturer. For the analyzed model of the engine the equivalent characteristic of minimum specific fuel consumption can be approximated with a small error with a linear function. It shows how speed should be referenced depending on load power. It is shown in Fig. 5, and the linear equation of approximated optimal speed ω_{d_opt} (in rad/s) is provided by (3). The minimum speed 120rad/s must be kept so as not to cause stopping of the engine, so below 8kW, the system operates with minimum speed. It may be assumed that engine power P_d on the shaft equals load power P_{Load}, and any difference in the optimal speed calculation will be compensated for by the incremental algorithm.

$$\omega_{d\_opt} = 0.008463P_d + 55.41 \tag{3}$$

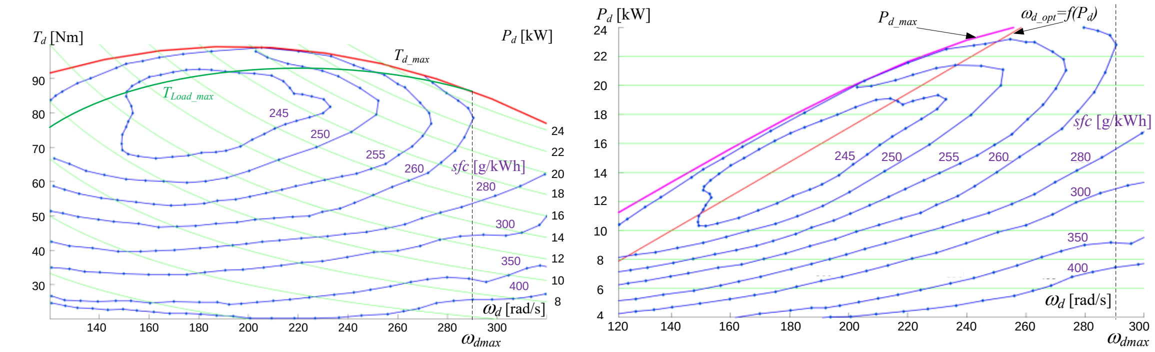

Fig. 5. Specific fuel consumption curves depending on a) driving torque and angular speed, and b) engine power and angular speed of the exemplary diesel engine KUBOTA V1505 (max power 25 kW at 290rad/s).

The optimal characteristic $\omega_{d\_opt}=f(P_{Load})$ from Fig. 5b, approximated here by a linear function, is specific for each model of the internal combustion engine, but it may vary during engine exploitation. Thus, this characteristic is used to find the initial operation point roughly, and next the elaborated algorithm is started to find the optimal operating point more precisely. The algorithm is a modification of maximum power point tracking methods for wind turbines [19][20] or photovoltaic sources [21][22], which are called perturbation and observation methods. For verification of the implemented algorithm, first it was necessary to build the fuel consumption model, based on the collected points of characteristics from Fig. 5a. Three dimensional segmented linear interpolation of specific fuel consumption as a function of the driving torque and angular speed $sfc=f\ (T_d,\ \omega_d)$ is shown in Fig. 6. This function can be implemented by a three dimensional look-up table.

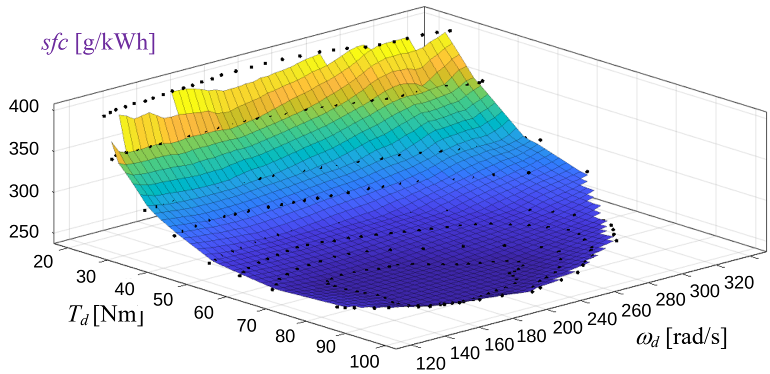

Fig. 6. Three dimensional segmented linear interpolation of specific fuel consumption as a function of driving torque and angular speed $sfc = f\ (T_d,\ \omega_d)$.

A more convenient way of sfc function implementation is its high order polynomial approximation. Fifth order polynomial approximation provides a relatively small error. The approximated function is shown in Fig. 7, and represented by (4). The implemented function requires information about diesel engine torque T_d, which in simulation is referenced from the speed controller, and actual speed ω_d, which in diesel engines is usually calculated based on the tooth wheel rotation. As a result, the function block returns the instantaneous value of specific fuel consumption *sfc* to be used by the incremental algorithm to find minimum *sfc*. In practice the value of *sfc* can be calculated based on the fuel consumption obtained from the engine controller and the load power obtained from the controller of the power electronic converter.

$$\begin{aligned} sfc(T_d,\omega_d) = {} & 3189 - 34.54\omega_d - 112.3T_d + 0.1803\omega_d^2 + 1.001\omega_d T_d + 1.722T_d^2 \\ & - 10^{-3}(0.4715\omega_d^3 - 3.693\omega_d^2 T_d - 11.69\omega_d T_d^2 - 11.78T_d^3) \\ & + 10^{-6}(0.6851\omega_d^4 + 5.444\omega_d^3 T_d + 29.66\omega_d^2 T_d^2 + 58.24\omega_d T_d^3 + 27.27T_d^4) \\ & - 10^{-9}(0.5094\omega_d^5 + 1.637\omega_d^4 T_d + 32.16\omega_d^3 T_d^2 + 39.05\omega_d^2 T_d^3 + 171.1\omega_d T_d^4 - 74.75T_d^5) \end{aligned} \quad (4)$$

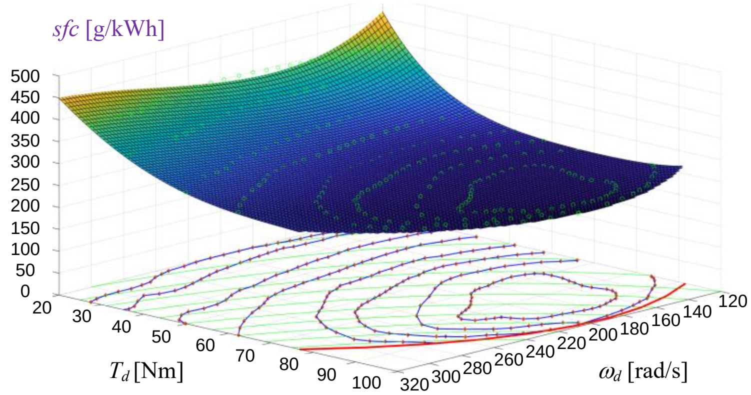

Fig. 7. Three dimensional fifth order polynomial approximation of specific fuel consumption as a function of driving torque and angular speed $sfc = f(T_d, \omega_d)$.

4. Incremental algorithm of minimum fuel consumption tracking

The average value of *sfc* is calculated with a 5s period. In real engine controllers, the *sfc* calculation is not as precise as in the simulated system, so the average value of *sfc* avoids noises and reduces inaccuracies. Moreover, the incremental algorithm cannot be as fast as the engine speed control loop, because it operates in outer loop in relation to the speed controller, therefore like in the wind turbine case, the incremental tracking algorithm is realized in relatively long cycles. Thus, based on the implemented three dimensional characteristic, tracking of the minimum *sfc* for a given load is relatively slow. This algorithm checks the level of *sfc* in previous *sfc(k-1)* and current *sfc(k)* five second calculation period and the sign of step of the engine reference angular speed $sgn(\Delta\omega_{d\_sfc}^{ref}(k))$. Based on this check, in the next five second calculation cycle, a positive or negative step of the reference speed is referenced, bringing the actual operation point closer to the optimal point for a given load. It has to be clearly noted that the algorithm is not designed to find the global minimum of the three dimensional *sfc* function, but to find the minimum value of *sfc* adequate for the actual load power. An important part of the algorithm is always to increase the speed when the loading current of the generator reaches the maximum. Maximal loading current i_{L_max} is obtained when the reference current reaches the maximum, that is when the outer voltage controller of the DC/DC converter reaches saturation. In this case the flag RU_{dc_sat} gets logical 1, and this is the information for the incremental algorithm not to find the minimum *sfc*, but to increase the speed, because of a temporary lack of power (Fig. 8).

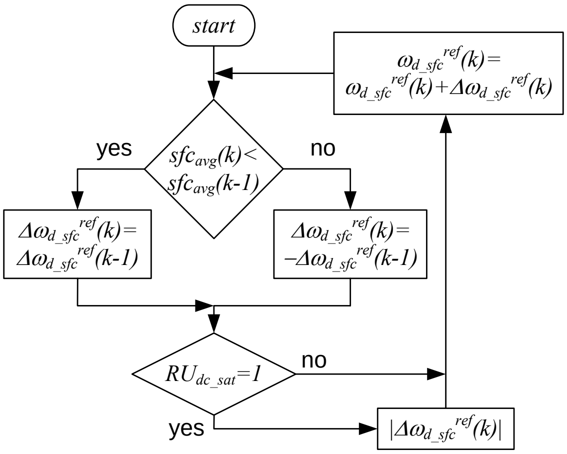

Fig. 8. Scheme of the incremental algorithm of minimum specific fuel consumption tracking.

In order to increase the dynamics of speed referencing during load step changing, the optimal characteristic $\omega_{d\_opt}(P_d) \cong \omega_{d\_opt}(P_{Load})$ is taken into consideration. Every change of loading power P_{Load} modifies the reference optimal speed ω_{d_opt}. However, the optimal speed may not be approximated precisely for each state of the engine, because many factors may influence specific fuel consumption curves. This is why ω_{d_opt} is treated as a rough value, and next the minimum *sfc* tracking algorithm is started from the new point to correct the final value of reference speed ω_d^{ref} by $\omega_{d\_scf}^{ref}$ depending on the real optimal point. The full control scheme of the diesel-engine-based generation system is shown in Fig. 9.

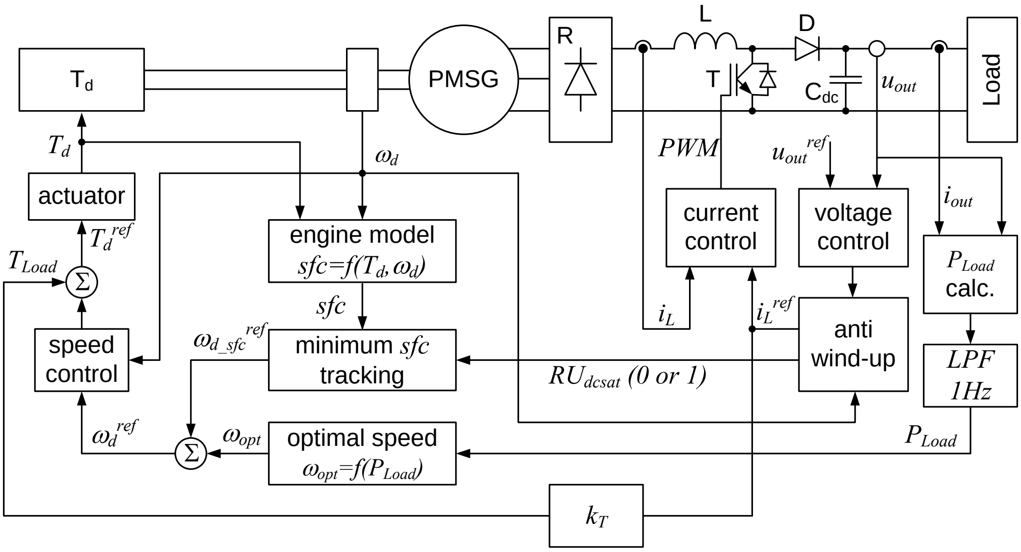

Fig. 9. Detailed scheme of the diesel-engine-based generation system control.

The role of flag RU_{dc_sat} must be explained, which is set to 1 when the boost converter current reaches its limit. The DC voltage proportional-integral PI controller references the current i_L^{ref} of the DC/DC boost converter. This current is responsible for loading torque T_{Load} of the generator. To make acceleration of the diesel engine to the new operating point during step loading possible, the maximum loading torque T_{Load_max} must be lower than the maximum driving torque T_{d_max} of the engine for each speed lower than the maximum (Fig. 5). The torque factor of the generator equals 2.4. The maximum driving torque is described by the function (5).

$$T_{d\_max} = 46.15 + 0.54\omega_d - 0.001413\omega_d^2 \tag{5}$$

Thus, the loading torque limitation curve T_{Load_max} (Fig. 5a) is assumed by (6), which is below T_{d_max},

$$T_{Load\_max} = 0.95T_{d\_max} + 0.03\omega_d + 4.5 \tag{6}$$

and due to the relation between the generator loading torque T_{Load} and generator current i_L equal to 2.4, the maximum generator current i_{L_max} equals (7)

$$i_{L\_max} = \frac{1}{2.4}T_{Load\_max} \tag{7}$$

Due to the large time constant of the electromechanical system in relation to the switching process of the power electronic converter, the current controlled DC/DC power electronic converter can be replaced with the controlled continuous current source. This source with a small error represents the converter and current controller. The reference signal of current i_L^{ref} produced by the DC voltage controller is provided directly to the steering terminal of the linear current source. This way the switching process of the transistor is avoided and the simulation step is increased to reduce the time of the calculation process made by the solver. A scheme of the simplified model is shown in Fig. 10.

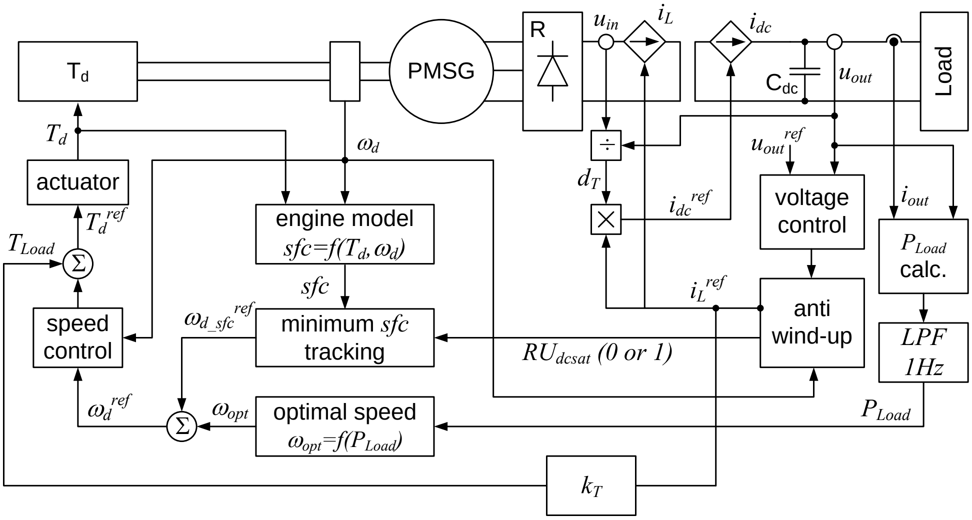

Fig. 10. Scheme of the simplified model with a diesel-engine-based generation system with a boost converter modeled with continuous current sources

The duty cycle of transistor switching equals the ratio between input and output voltage, with neglect of the voltage drop on inductor resistance. Due to equality of input and output power in the steady state, the instantaneous power is calculated as (8).

$$p_{in} = p_{out} = u_{in} i_L = u_{out} i_{dc} \tag{8}$$

The i_{dc} current flowing into the DC circuit representing the average value per switching period of the discontinuous diode current, is calculated simply by (9)

$$i_{dc} = \frac{u_{out}}{u_{in}} i_L \tag{9}$$

It has to be noted that loading current i_L of the inductor equals the reference value i_L^{ref}, and the i_{dc} current equals i_{dc}^{ref}. Further simplification is possible by replacement of the electric machine and diode rectifier with the mechanical load with controlled torque (Fig. 11), considering Eq. (2) as the relation between reference current and reference toque for such controlled mechanical load.

Electric load power can be different than the generator power in the case in which the power system is supported by energy storage on the DC side. Knowing the electrical load power P_{Load}, the optimal speed for this power can be reached immediately after load step change, so speed control can be faster than if generator power P_{gen} is taken into consideration. However, when the system is not equipped with energy storage, there are small differences in speed control transients between P_{Load}, and P_{gen} used for optimal speed calculation.

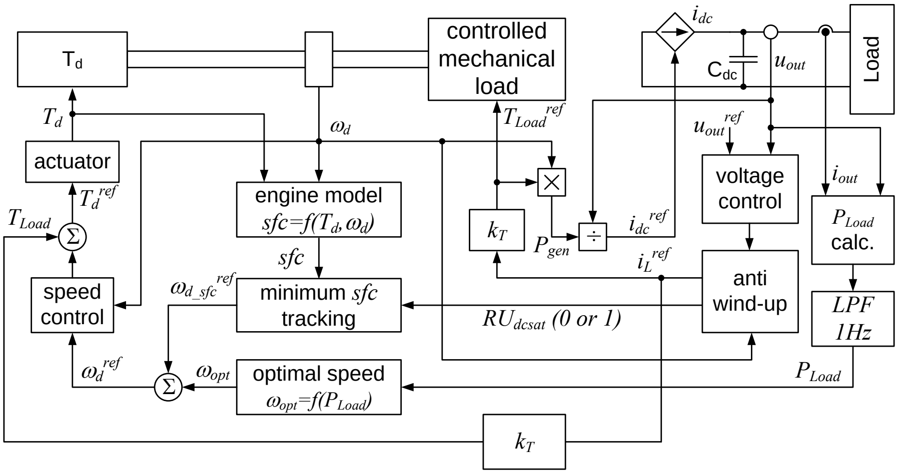

Fig. 11. Scheme of the simplified model with a diesel-engine-based generation system with the PMSM generator modeled as controlled mechanical loading torque.

5. Simulation results of the diesel-engine-based generation system

Simulation results have been obtained by implementation of the *sfc* approximating polynomial function and the incremental algorithm in C language. Two C blocks were used in PSIM software v. 11.0.3 dedicated for simulation of electrical and mechanical systems, power electronics and control. Fig. 12 presents the results in a short time period in the steady state. Details of waveforms during every five second cycle of the incremental algorithm can be seen. Every 5rad/s step change of reference speed causes small damped oscillations of real speed ω_d, output DC voltage u_{out}, diesel torque T_d, and loading torque T_{Load}. Load power P_d

varies slightly, due to constant load resistance used in this test. However, power oscillations are negligible.

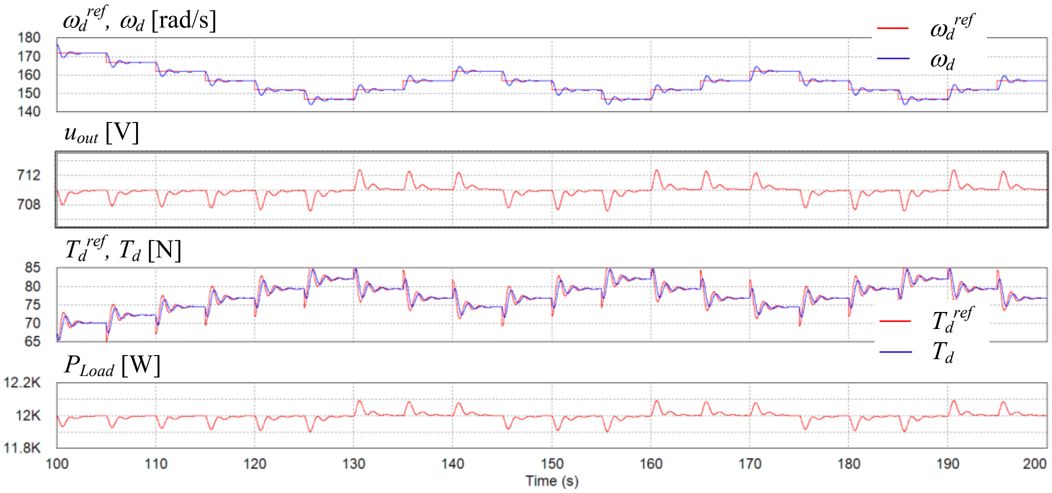

Fig. 12. Simulation results of a variable speed diesel-based generation system with speed referenced by the incremental algorithm of minimum specific fuel consumption tracking.

To reduce the oscillations of speed, torque and DC voltage, the incremental algorithm is modified in the following manner. The speed change $\Delta\omega_{d\_sfc}^{ref}$ as the output signal from the incremental algorithm is not referenced by steps, but by linear change, as it is shown in Fig. 13. Instead of steps, a linear function is used, and the oscillations of speed and engine torque during every cycle are minimized. It also results in smoother output voltage. This type of reference speed change can also be used in standard maximum power point tracking algorithms in wind turbines, and it causes reduction of torque peaks during every change of the reference speed. However, wind turbine operation issues are beyond the scope of this paper.

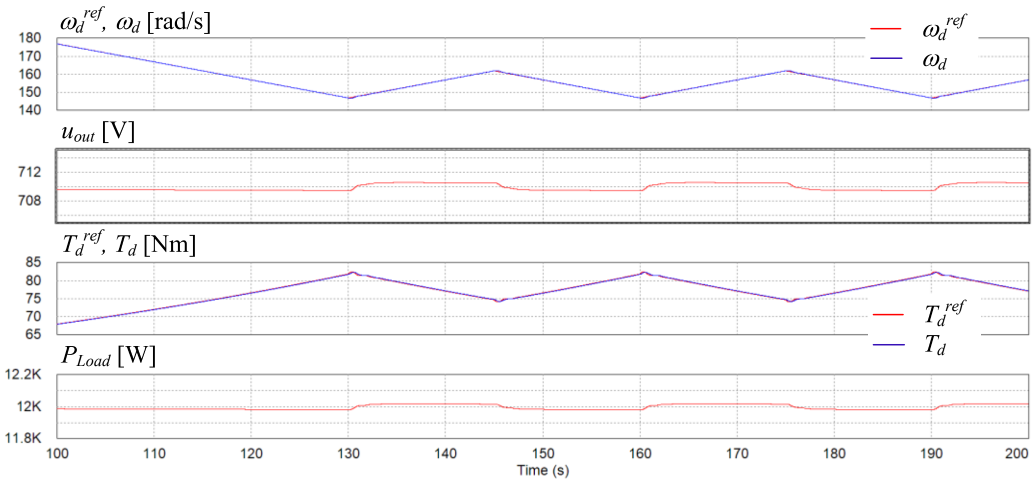

Fig. 13. Simulation results of a variable speed diesel-based generation system with speed referenced by the incremental algorithm of minimum *sfc* tracking with a modified speed correction signal – long time scale.

When the optimal speed function is assigned precisely, it is obvious that the incremental algorithm is not necessary. However, many factors such as fuel quality, temperature, altitude of engine installation, and other, may cause that the selected optimal speed is not matched perfectly to the loading power, and minimum *sfc* for a given load power is not reached. Fig. 14 presents a comparison of the classic method, in which the optimum speed function (3) from Fig. 5b is moved down by 10%, and the method equipped with the incremental algorithm operating as a correction part of the reference optimal speed calculation.

It is observed that the assumed 10% of inaccuracy of optimal speed function, for half of the rated load power in this particular test, causes 4% higher fuel consumption than in case of the incremental algorithm used as a correction part of control. The diesel engine speed is matched more precisely to obtain lower fuel consumption for the same power. It has to be noted that the incremental algorithm does not need precise information about the value of fuel consumption, but it bases on the difference between fuel consumption in the current and previous step. It means that it is not sensitive to errors like offsets, but it is sensitive to noises when the calculation step is short. This is why the average value of fuel consumption is calculated during 5s periods, and the algorithm cannot be very fast. Thus, the algorithm is used as a supplementary part to optimum speed control, and not as the main part.

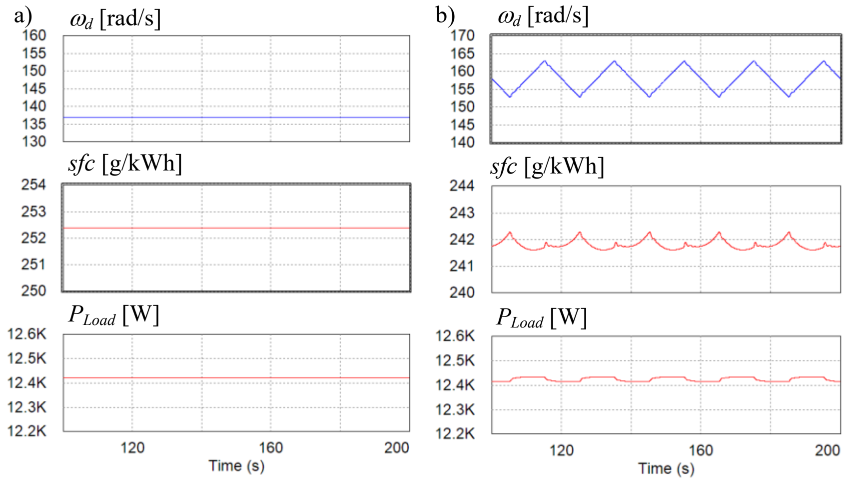

Fig. 14. Steady states for 12.4kW of loading power for a) disabled, and b) enabled incremental algorithm.

The incremental algorithm can find the optimal speed without pre-calculation of optimal speed, but it takes a lot of time during a load step change, because of slow dynamics of the algorithm. Thus, the part with optimal speed determination remains unchanged. This way, speed change transients are short during a step change of power. Fig. 15 presents the step change of load power from 12kW to 24kW in 75s of the simulation and back from 24kW to 12 kW in 225s of the simulation. Fast speed response is obtained not only due to optimal speed calculation but also by implementation of loading torque feed-forward structure described in Section 2. Output voltage dip in 225s after step loading is caused by limitation of the generator current and lack of energy in this state until the engine reaches a higher speed required for increased load. Fig. 16 presents the engine power vs. speed trajectory and engine torque vs. speed trajectory obtained for the tests from Fig. 15. Two areas of steady state operation can be seen, marked by circles.

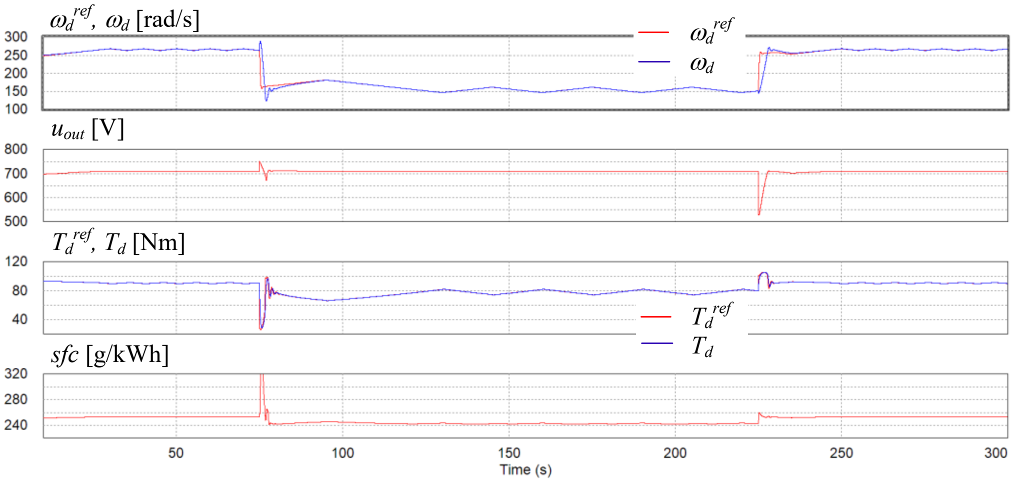

Fig. 15. Waveforms of reference and actual speed, output DC voltage, reference and actual engine torque, and specific fuel consumption during steady states and transients of loading power change from 12kW to 24kW.

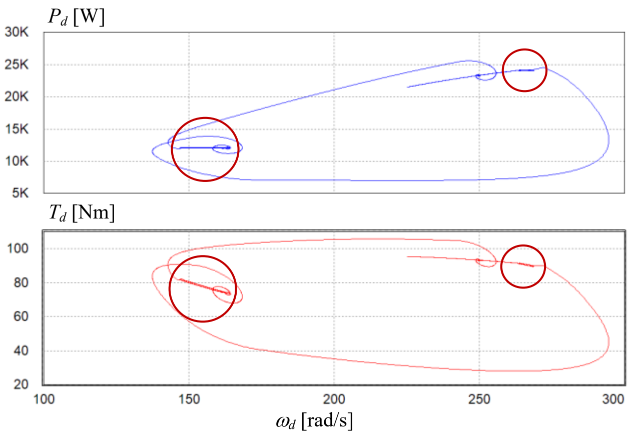

Fig. 16. Engine power P_d and torque T_d curves vs. engine speed ω_d, during the test from Fig. 15.

In the presented case shown in Fig. 16, one can see continuous searching of the minimum *sfc* by the incremental algorithm in the two steady state points. The algorithm is working all the time, but in the case when power equals the maximum (25kW) or is lower than 8kW, the speed should be maximum or minimum respectively, and the incremental algorithm should not disturb the final value of reference engine speed ω_d^{ref}. Fig. 17 presents the results when power changes from the maximum (25kW) to 6kW. For 25kW the engine operates with maximum speed 290rad/s, and for 6kW the engine operates with minimum speed 120rad/s.

The elaborated incremental algorithm is working slowly to find the minimum specific fuel consumption for different load power. It is difficult to find the totally random load, because any load is switched on and off in relatively long times. However, even with fast and random changes of load power the algorithm cannot get lost. A situation is not allowed in which the algorithm continuously increases or decreases the reference speed in relation to the calculated optimal speed.

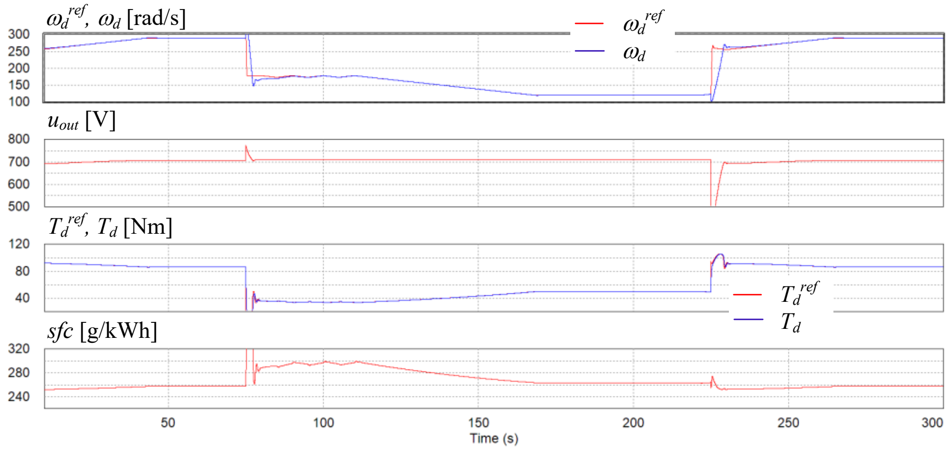

Fig. 17. Waveforms of reference and actual speed, output DC voltage, reference and actual engine torque, and specific fuel consumption during steady states and transients of loading power change from 6kW to 25kW.

Such situation could stop the engine or cause the maximum engine speed even if not needed. Moreover, the algorithm should not increase the average specific fuel consumption at this state (random loading power). As it can be seen from Fig. 18-19, there is no visible difference in the average *sfc* when the incremental algorithm is disabled (Fig. 18) and enabled (Fig. 19). The obtained difference of *scf* (0.12g/kWh) in favor of the enabled incremental algorithm is not representative and it is at the level of numerical error. However, these tests are not intended to show the advantage of the incremental algorithm, but to show its stability even for random load. It has to be clearly noted that such random and large short-term variation of load power is rare in practice, but for such kind of load variation, implementation of the elaborated incremental algorithm does not make sense, because it cannot help decrease *sfc*. In these tests, the optimum speed calculation is made without 10% error assumed in the tests results shown before. The frequency of load variation equals 0.07Hz, so the time step is ca. 14s, which is not a multiplicity of the incremental algorithm time step. This is to avoid artificial overlapping of the load change cycles with incremental algorithm cycles.

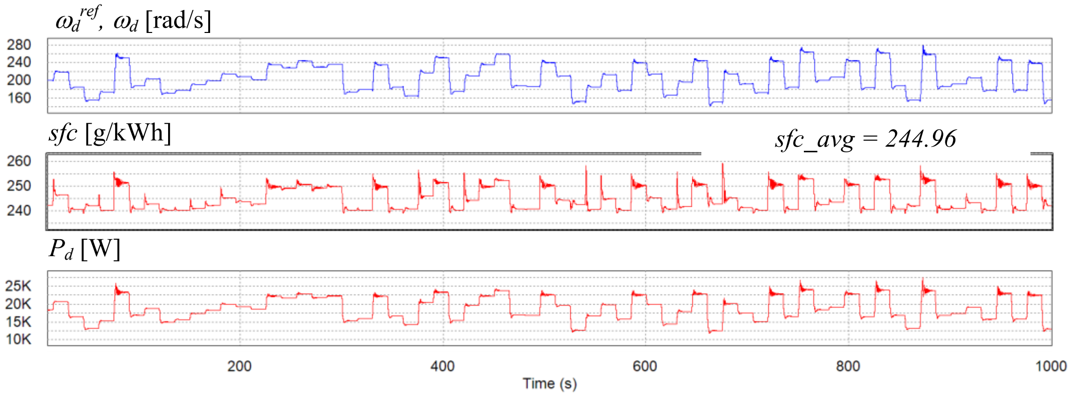

Fig. 18. Response of the diesel engine speed for the case of random load power with the disabled incremental algorithm and precise calculation of the optimal speed.

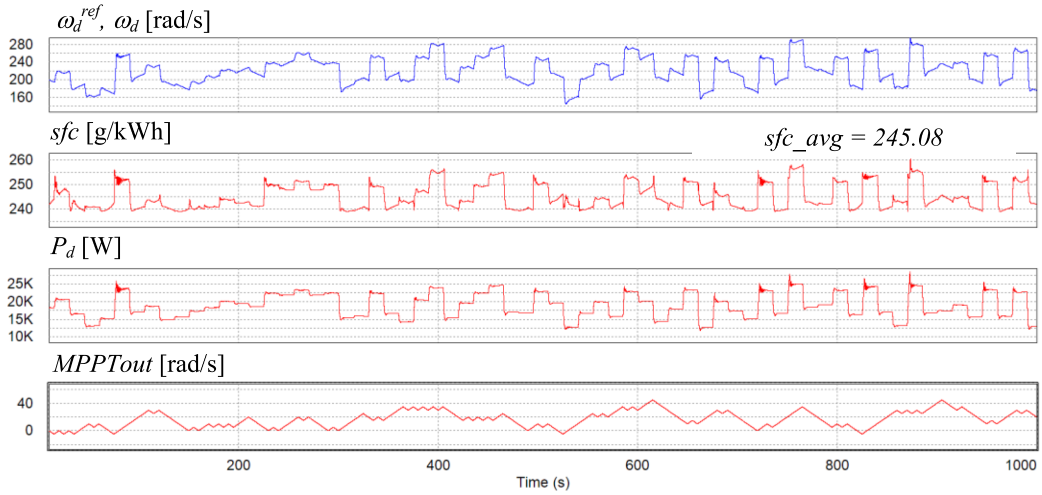

Fig. 19. Response of the diesel engine speed for the case of random load power with the enabled incremental algorithm and precise calculation of the optimal speed.

6. Conclusion

The paper presents an original concept of the use of the incremental algorithm to find the optimal operating point giving minimum specific fuel consumption of the diesel-engine-based variable speed generation system. The proposed control provides short transients of the output voltage during load changes and it takes into consideration adequate limitation of the loading torque in the whole range of speed to allow engine acceleration during load power change. The fundamental part of the reference speed signal originated from the roughly approximated function of optimal speed vs. loading power taking into consideration minimum specific fuel consumption for a given load power. The function may vary during engine exploitation and strongly depends on the content of the fuel quality. The role of the incremental algorithm is to correct the reference speed to obtain an optimal operation point closer to the ideal one giving the true minimum specific fuel consumption *sfc* for a given load power. The algorithm does not perturb speed referencing for small and maximum power, when the engine speed should be minimum or maximum respectively, and it is resistant to the random load profile. Short transients of speed control can be obtained by implementation of loading torque feed-forward behind the engine speed controller, which takes the role of disturbance rejection.

Symbols and Abbreviations

T_d – driving torque of the diesel engine
T_{Load} – loading torque of the generator
T_{Load_max} – maximum value of the loading torque limited by maximum current of DC/DC converter
ω_d – angular speed of the diesel engine
ω_d^{ref} – reference angular speed of the diesel engine
ω_{d_opt} – optimal angular speed of the diesel engine for a given load power (approximated rough value)

$\omega_{d\_sfc}^{ref}$ – reference correction of the angular speed produced by the incremental algorithm
$\Delta\omega_{d\_sfc}^{ref}$ – step of the reference correction of the angular speed
P_d – diesel engine delivered power
P_{Load} – electric load power
sfc – specific fuel consumption
i_L – input current of the DC/DC converter
i_L^{ref} – reference input current of the DC/DC converter
i_L^{ref} – reference input current of the DC/DC converter
i_{L_max} – maximum value of the input current of the DC/DC converter
u_{out} – output DC voltage
i_{Load} – load current
m_f – mass of fuel
RU_{dc_sat} – flag indicating the DC voltage controller saturation (obtained maximum current of DC/DC converter, and simultaneously maximum loading torque)
outREG – output signal from engine speed controller
LPF – low pass filter

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