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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 electronics 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 three-dimensional approximation of fuel consumption characteristics.

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].

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 of engine to the actual demanded power. Variable speed operation of the internal combustion engine, like variable speed wind turbines, requires a dedicated power electronic 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

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Nomenclature

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
$\omega_d{}^{ref}$	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

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.

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. 230 V, 50 Hz). An intermediate DC bus decouples two electronic systems and makes it possible to keep the generator frequency different than the grid/load AC voltage frequency. 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 converter does not matter, due to the fact that the speed control loop is much slower than possible current and torque ripples of the generator caused by converter operation.

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 taken by the DC/AC converter for the load (average value of instantaneous power) is important, because it determines the average value of rectifier current, so the generator average torque, at a given engine speed. From this point of view, the DC/AC converter can be replaced by resistive load in a simulation. The generator current (so the loading torque) is controlled entirely by the boost converter, and only this part of the power electronics 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

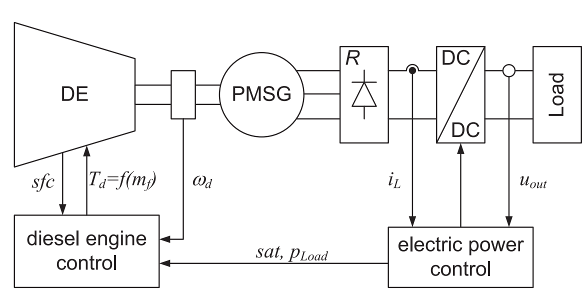

Fig. 1. General scheme of an internal-combustion-engine-based generation unit with a power converter.