Power Balance Control for Stand-alone Generation Systems via an AC/DC/AC Power Electronic System

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1. Abstract

This paper presents the research work on a stand-alone diesel engine driven permanent magnet generator system. A new control strategy has been studied to keep a permanent generator based generation system operating steadily and to provide system consumers with the good quality power. An AC/DC/AC power electronic conversion system is introduced and a power balance based control strategy is presented for the studied stand-alone system so that the system can be operated at variable speed while maintain the voltage output to the load with almost constant amplitude and frequency under varying load conditions.

2. Introduction

In a power system the electrical load tends to vary in a more or less regular way over the day, often reaching a maximum sometime during normal working hours and falling to a low level in the very early hours of the morning. As well as the gradual changes, there are also fluctuations of much shorter duration caused by switching in or out large electrical equipment. There may also be substantial changes in the load with the time of week and with the season of the year.

The ratio of any load-changing step to the system power capacity in a stand-alone system is normally larger than that in a power network significantly. Therefore, load changes can cause the system to more readily depart from the desired operating condition, especially in stand-alone systems with small generators of power rated less than 10 kW. The key issue of controlling such a system is to satisfy the load-change requirements and to maintain the system at the desired operating condition, which means that the voltage and frequency of the system have to be kept nearly constant for the electricity appliances in the system. Also the system is operated reliably and efficiently.

In this paper, a proposed power electronic interfaced diesel engine driven permanent magnet (PM) generator system configuration has been adopted as shown in Figure 1. An AC/DC/AC power electronic conversion system is formed as a interface between the generation system and load, and a power balance based control strategy is proposed for the studied stand-alone system. With this configuration and the control strategy the control targets have been achieved by speed regulation and controls of the AC/DC/AC power electronic conversion system. In the following sections the principle is discussed and some simulation results are presented.

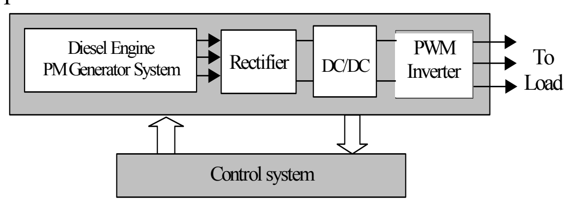


Figure 1. Schematic of a stand-alone diesel engine driven PM generator system

3. System operation principle

In a stand-alone power system, the amount of electricity generated needs to balance that demanded by the consumers. As the load increases or decreases, the power output, and so the amount of fuel input, has to be adjusted in order to satisfy the consumer demand and maintain the system operating in a stable condition.

To operate a diesel engine generator system efficiently, the speed of the engine and generator has to be varied with changing load. To realise this, a speed governing system plays an important role, controlling the fuel input of the engine and hence the engine and generator speed. The diesel engine governing system controls the engine speed by adjusting fuel flow, so as to control the generator output and provide sufficient power to match the demand.

3.1. The diesel engine system

The diesel engine system is a non-linear system. The general engine and load torque/speed characteristics are shown in Figure 2.

As shown in the figure, if the engine is not governed, then when the load is changed the speed will change correspondingly, for a load decrease there is a speed increase and visa versa. If the load is changed by a small amount δG_L (e.g. by a small increase) when the engine is running at equilibrium point 'α', the engine is so governed that the fuelling rate is varied by an amount δq in response, then a new equilibrium point 'β' will be achieved associated with a small speed change $\delta\omega_0$. The final change in the driving torque is given by:

$$\delta G_E = \left(\frac{\delta G_E}{\delta\omega_0} \right)_q \delta\omega_0 + \left(\frac{\delta G_E}{\delta q} \right)_{\omega_0} \delta q \tag{1}$$

The variation of load torque after taking speed variation into account is:

$$\delta G_L = \Delta G_L + \left(\frac{\delta G_L}{\delta\omega_0} \right)_L \delta\omega_0 \tag{2}$$

For equilibrium

$$\delta G_E = \delta G_L \tag{3}$$

which means that a steady system requires the load torque match the driving torque. It is also indicates that when load changes a corresponding fuel change, i.e. the input power change is needed to balance the system power generation and the power consumption.

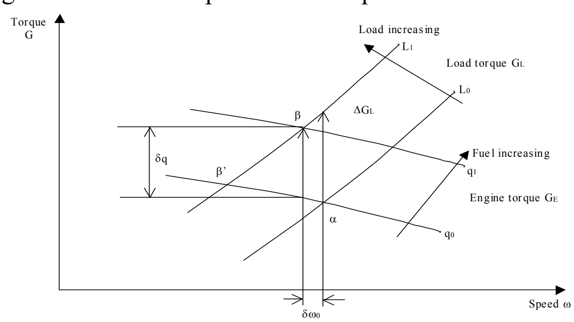


Figure 2. Speed and torque change with varying load.

3.2. The PM machine

The field controlled synchronous generators and permanent magnet generators are different. The fundamental difference is that field controlled synchronous generators can achieve voltage regulation by controlling the field excitation current, but permanent magnet generators normally have no adjustable excitation systems. Due to this reason, different methods must be used to regulate the system voltage. Basically the voltage of a permanent magnet generator may be adjusted by controlling the speed of the prime mover (engine) to produce a variable EMF. One fundamental concept to be considered is that the system has to balance the power supplied and the load plus power losses in order to keep a system stable. The key aspect in controlling a stand-alone generation system is to produce the power demanded by the load. Therefore, whenever a load change occurs the generated power needs a corresponding adjustment quickly to balance the power requirement and maintain the system stability.

Based on equations (1), (2) and (3), the equation (4) can be derived as

$$\delta\omega_0 = \frac{\left(\frac{\delta G_E}{\delta q} \right)_{\omega_0} \delta q - \Delta G_L}{\left(\left(\frac{\delta G_L}{\delta\omega_0} \right)_L \delta\omega_0 - \left(\frac{\delta G_E}{\delta\omega_0} \right)_q \right)_L} \tag{4}$$

Equation (4) shows the system may be controlled to operate at an almost constant speed ($\delta\omega_0 \cong 0$), or variable speed ($\delta\omega_0 \neq 0$) by adjusting the fuelling rate δq.

3.3. The overall system configuration and operation

Although a stand-alone diesel engine driven PM generator generation system carrying a significantly changing load in the normal operating range can be in fixed speed operation but may not be efficient. On the other hand, even though the voltage regulation may be achieved by varying the engine speed, however the response would be relatively slow as the mechanic systems tend to retain.

The system may be operated more economically if the engine is operated at the most efficient point in its normal working range. This leads to the concept of variable speed operation of the generation systems and the introduction of a suitable electronic interface between the machine and power systems so as to the voltage and frequency to be maintained constant.

Figure 3 shows the proposed overall control strategy for the stand-alone generation system. The complete generation system comprises a prime mover, a PM generator and power electronic converters. The prime mover with variable speed controller provides an appropriate driving power to meet the demands of the changing system load, while the dc-dc conversion system absorbs voltage transients and maintains the voltage at the dc terminal of the inverter within desired range, the frequency of the ac loading system being maintained by the inverter.

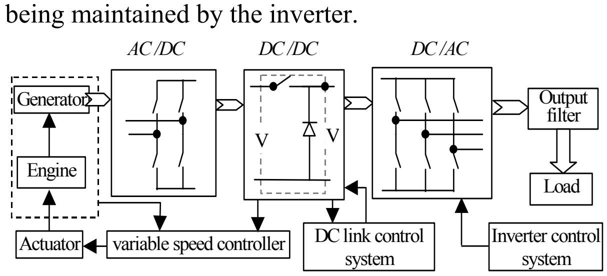


Figure 3. Stand-alone diesel engine generator system with AC/DC/AC interface

In Figure 3 the power electronic system in the stand-alone generation system provides an effective solution to the voltage control. In the proposed scheme, the ac voltage produced by the generator is rectified into dc and the dc-dc converter provides the controlled dc voltage to the inverter. The regulated dc voltage is then converted back into ac using a PWM (Pulse Width Modulation) inverter [2][3][4][5]. The power electronic systems required and associated control methods are briefly described to highlight their functions in the integrated system.

In the system, the rectifier is an uncontrolled rectifier, so that the voltage at its output terminal changes while generator output voltage varies. The use of an uncontrolled rectifier can reduce the cost and complexity of the control system.

The dc-dc converter functions as a dc transformer, its ratio varies with its input voltage. A variable ratio dc-dc conversion stage allows the diesel engine and generator to be operated at variable speed, i.e. allows a changing voltage at dc link rectifier terminal, but the voltage on the inverter side remains almost constant. The controllable dc-dc conversion stage decouples the frequencies of the two ac systems.

The dc to ac conversion in this system is achieved using a three-phase bridge power electronic inverter. The inverter is connected to the output terminal of the dc link to provide the desired ac voltage and frequency.

In summary, the rectifier in the system is a non-controlled device, the dc-dc converter has a feed back control system and the inverter is controlled by a fixed frequency and amplitude modulation switching strategy. With the combination of a dc-dc converter with variable conversion ratio and a voltage source inverter with the fixed modulation ratio, an effective appropriate power supply is provided. These power electronic conversion systems are co-ordinated with the fuel governing mechanics to minimise the transient disturbance. The fuel control aims to maintain the stable and efficient operation of the system, while the dc link chopper control seeks to provide the voltage source inverter with an almost constant dc voltage input, so that a fixed modulation ratio can be applied to the VSI. The generator itself is de-coupled in frequency from the ac load that receives the required power with relatively constant voltage amplitude and frequency. The control subsystems are cooperated together within an overall control strategy for the stand-alone generation system.

4. Overall system modelling and simulation

The complete system control consists of three main parts:

- A closed-loop control system for the prime mover and generator system to perform the control of the speed and the input power.
- A closed-loop control system for the dc-dc voltage converter to regulate the dc link voltage.
- A voltage source inverter with the associated PWM control system to provide the ac voltage with constant amplitude and frequency to the load.

The proposed system, including engine, generator, power electronic converters and the control systems, has been modelled, and the overall system simulation has been performed.

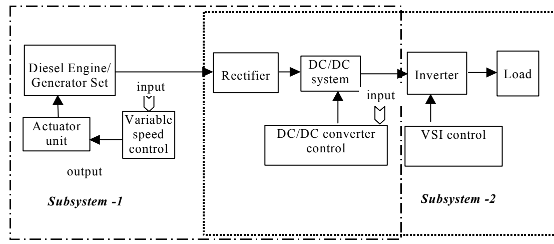
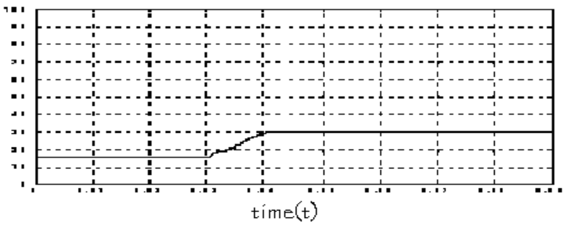


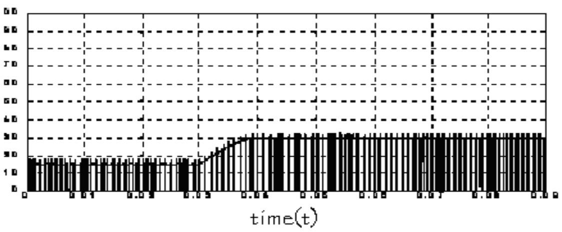
Figure 4. Block diagram of the simulation system

The whole simulation system is made with two subsystems for efficient simulation, as shown in Figure 4. Subsystem-1: the diesel engine-generator system and part of power electronic system including ac-dc and dc-dc conversion, the speed controller and dc converter control. A resistive load is used to load the dc-dc converter. Subsystem-2: the power electronic system composed of the rectifier, dc-dc converter, inverter and the associated control system for power electronics. The overlap of the two subsystems is designed to enable the effectiveness of the control systems to be demonstrated.

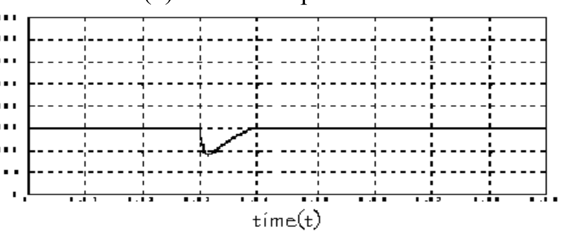
The simulation results are presented in Figure 5. In the simulation the load current is doubled at 0.03 seconds as shown in figure 5 (a). Following the disturbance, the fuel input control is then adjusted. The action brings the system to the new speed and produces more power. In Figure 5 (b), it can be seen that the input current increases correspondingly to supply the load requirement. It is also noted that the input current contains rich current pulses due to the chopper switching. Figure 5 (c) shows the output voltage drops when the change of the load current occurs, however, the control system adjusts the ratio of switching duty cycle to bring the output voltage back to the reference level. The input voltage to the inverter is kept at constant level during the period of simulation, as shown in Figure 5.18 (d). The chopper switching causes the ripples in the input voltage. A high degree of ripple appears when a larger current is delivered after the change of the load current. Figure 5 (e) shows the inverter output line-line voltage waveform of a space vector PWM scheme. With the constant inverter input and fixed modulation ratio the voltage output can be kept in a good quality. The results of the presented case study demonstrated the effectiveness of the power electronic conversion system, the associated control system and the integrated system control strategy.



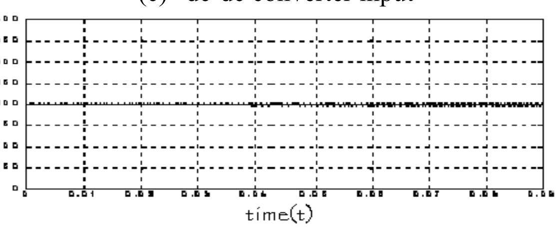
(a) Load current (average value)



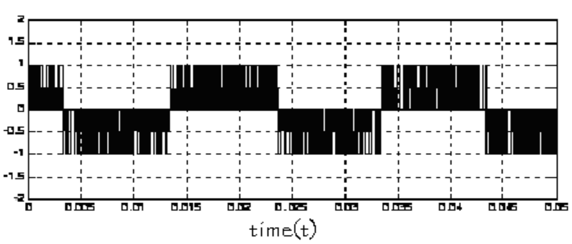
(b) Dc-link Input current



(c) dc-dc converter input



(d) Inverter input voltage



(e) Inverter output line-line voltage

Figure 5. The simulation results are presented

5. Conclusions

The control strategy has been developed by integrating the sub-controllers (i) Fuel input control, (ii) Power electronic converters control. The investigation and evaluation of the system and control strategy have been performed by simulation. The simulation results show the proposed combined control strategy for the whole control system performs well. In terms of the system power balance, as load increases, the speed controller adjusts the operating speed to a higher level so as to generate more power to balance the load increase. In the proposed control strategy, keeping a constant dc link voltage is an important condition for providing an adequate voltage to the consumer in the ac system, this has been secured by a dc-dc converter and a fixed modulation ratio switching PWM inverter. The chopper controller can respond quickly to the system dynamics and therefore quickly provides control of the DC link voltage. The mismatch between the high speed system transient and moderate speed response of the speed control is compensated for by the chopper.

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