Simulation of dynamic modes of power supply systems equipped with diesel generators, at inferior power quality

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Abstract. The article provides results of studies aimed at implementation of power supply systems (PSS) computer-based models in conditions of inferior power quality, where the PSS include backup diesel generators. The main aim of the study was to research these generators synchronization with the PSS network. The simulation was performed in the MATLAB environment using the Simulink and SimPowerSystems software packages. Based on the results obtained, it can be concluded that the self-synchronization method can be used for turning on diesel generators for parallel operation with PSS. After the synchronization processes completion, an improvement in the quality indicators of electricity in the PSS network and at the interfaces with the power supply system in terms of asymmetry and harmonic distortions.

1. Introduction

The power supply systems (PSS) of industrial enterprises can use their generators, for whose actuation, internal combustion engines can be used, as well as hydraulic and wind turbines. They can act as the primary power sources of consumers located remotely from the consumers’ infrastructure network [1], as well as to backup power supply of facilities that require a particularly reliable electricity supply. The most common are diesel power plants [2].

On the background of the power generation industry digitalization, the task of creating PSS digital models that provide adequate modelling of stationary and transient modes is of particular relevance.

The article presents the results of studies aimed at the implementation of computer models of power supply systems, which include backup diesel generators. The simulation was performed in the MATLAB environment using the Simulink and SimPowerSystems software packages. The main aim of the study was to research these generators synchronization with the PSS network.

2. Simulation procedure

When studying transient processes of a diesel generator unit (DGU), it is necessary to take into account the amount of fuel supplied to the diesel cylinder, which determines its torque during the entire subsequent piston stroke. In other words, the DGU power control occurs with some delay, which must be taken into account.

The main elements of DGU are the internal combustion engine, controllers, the excitation system...
and synchronous generator. The general DGU block schematic diagram is shown in Figure 1. A speed deviation generates a control signal, as a result of which the torque of the prime engine is changed.

A diesel engine produces a torque determining the mechanical power as follows:

\[ P_{\text{mech}} = \omega T_e, \]

where \( \omega \) – rotor rotational angular frequency, rel.u.; \( T_e \) – engine torque, rel.u.

**Figure 1.** DGU block schematic diagram.

Speed controller responses to the signal of its deviation and are designed to maintain the set engine speed mode. It is the primary means of on-load control. Speed control, as a rule, is simulated using the lead/lag transfer function:

\[
W_{SC} = \frac{K \cdot (T_1 s + 1)}{T_2 s^2 + T_3 s + 1},
\]

where \( K \) is the gain; \( T_1, T_2, T_3 \) – time constants.

The control system, assisted by the actuator drive, controls fuel supply to engine cylinders. Drive model implementing the lag when fuel supply is changed, and reduction or increase in the torque, subject to a sign of changing the amount of fuel supplied to cylinders, was represented by the following transfer functions:

\[
W_{Dr} = \frac{T_4 s + 1}{T_5 s + 1} \cdot \frac{1}{T_6 s + 1} \cdot \frac{1}{s},
\]

where \( T_4, T_5, T_6 \) – the drive time constants.

A lag link models the engine:

\[
W_{En} = e^{-T_7 s},
\]

where \( T_7 \) is the delay time of the engine in its translation to the mechanical energy of a synchronous generator.

The main goal of the excitation system control is to maintain the generator voltage. For diesel generators, as a rule, the most straightforward excitation system is used. For domestic DGU, the following types of excitation systems are used:

– based on a three-winding summing transformer with a magnetic shunt and a controlled thyristor-diode converter (figure 2);

– brushless with synchronous diode exciter, a magnetoelectric exciter with permanent magnets and a static thyristor excitation regulator (figure 3).

As the DGU excitation system, the model used the standard MATLAB unit of the excitation system with a regulator, which is a system that implements a direct current exciter described in [3]. The main elements that make up the excitation system are the voltage controller and the exciter.
Figure 2. Brushless diesel generator excitation system with three-winding summing transformer and magnetic shunt.

Figure 3. Brushless diesel generator excitation system with magnetolectric subexciter using permanent magnets.

The excitation system model consists of the following units:
- units for selecting the effective voltage value and low-frequency filter with the transfer function $1/(0.02s + 1)$;
- time delay compensation unit with the transfer function $(T_s s + 1)/(T_s s + 1)$;
- the main controller unit with the transfer function $K_a/(T_s s + 1)$;
- rectifier unit with the transfer function $1/(T_s s + K_a)$;
- damped feedback unit with the transfer function $0.01s/(0.1s + 1)$.

The DGU synchronous generator is represented by the standard MATLAB unit, which implements a model of a synchronous machine with a damper winding. The value of the inertial constant of the DGU generator which is used in the simulation $H = 7.83$ s.

3. The simulation results
The simulation was carried out concerning the facility diagram shown in figure 4. The PSS includes two 110/10 kV transformers energizing 10 kV busbar sections of the main step-down substation. The primary power consumers are asynchronous electric motors (ASM) of 10 and 0.4 kV. A large branching characterizes the electrical network of the facility. The low-voltage ASM groups are powered by overhead and cable lines of 10 kV with voltage reduction to 0.4 kV using transformers. There are three DGU at the facility with the capacities indicated in Figure 4. An equivalent static active-inductive loading was taken into account for 10 kV and 0.4 kV ($\hat{S}_1, \hat{S}_2$) during PSS model development.
When simulating, the power supply of all loads was carried out from the PSS, and the synchronization of DGU with the network was performed. In this case, the method of generators self-synchronization was considered. Because all DGU has the same power, loading and distribution of the load power between them were carried out evenly immediately after synchronization with the network. Simulation results are given in Figures 5–8 and in Tables 1, 2.

Figure 5 shows the nature of the frequency change in the PSS when the DGU is turned on by self-synchronization method. Frequency deviations were observed in the range \(-0.1\) to \(+0.1\) Hz, which attenuated within 4 s. In the steady-state after synchronization, the power of DGUs reached 85% of the nominal value.

Figure 6a shows the time dependence of the rotor frequency of one of the DGU. Frequency deviations were observed in the range \(-2\) to \(+1\)% of the nominal value. Figure 6b shows the DGU voltage dependence on time, showing that the steady-state value was reached within 5 s.

Figure 7 shows the time dependences of the DGU generator currents. The oscillograms of the active and reactive powers at the input of 10 kV of the supply substation are shown in Figure 8.
**Figure 6.** Changing the DGU generator rotor frequency (a) and oscillograms of the effective values of voltage of the DGU generator (b).

**Figure 7.** Oscillograms of the effective and instantaneous values of the DGU generator currents.

**Figure 8.** Oscillograms of active and reactive powers at 10 kV input of supply substation.
The provided results allow making the following conclusions:
1. The introduction of diesel generators in parallel operation with the facility PSS can be performed by the self-synchronization method.
2. The transition process of an oscillatory nature is completed within a period not exceeding 6 s.
3. When the DGU generators are turned on for parallel operation with the PSS network, the electrical energy quality indicators improve (Table 1, 2).

| Table 1. Coefficients of harmonics and negative sequence asymmetry on 110 kV buses, % |
|-----------------------------------------------|
| PSS mode                                      | $k_{2UL}$, % | $k_{U_{AB}}$, % | $k_{U_{BC}}$, % | $k_{U_{CA}}$, % |
| Without DGU                                  | 2.00         | 6.38            | 7.42            | 6.77            |
| For energized DGU                            | 1.92         | 5.76            | 6.65            | 6.32            |
| (generator load was 85% for each one)         |              |                 |                 |                 |
| Difference, %                                | 4.0          | 9.7             | 10.4            | 6.6             |

| Table 2. Coefficients of harmonics and negative sequence asymmetry on 10 kV buses, % |
|-----------------------------------------------|
| PSS mode                                      | $k_{2UL}$, % | $k_{U_{AB}}$, % | $k_{U_{BC}}$, % | $k_{U_{CA}}$, % |
| Without DGU                                  | 1.53         | 4.92            | 5.68            | 5.21            |
| For energized DGU                            | 1.43         | 4.56            | 5.26            | 4.89            |
| (generator load was 85% for each one)         |              |                 |                 |                 |
| Difference, %                                | 6.5          | 7.3             | 7.4             | 6.1             |

4. Conclusion
Digital models of a power supply system equipped with backup diesel generator units have been developed. Its components can be used for the quick implementation of PSS digital models of other facilities that include diesel generators. The practical significance of the development lies in the possibility of improving dynamic processes in the PSS, applying simulation results in the development and tuning of excitation and rotation automatic controllers [4] of DGU generators.

Based on the developed model, digital twins [5, 6] of power supply systems equipped with backup diesel generators can be designed. In the digital twin, the model parameters are refined using information coming from measurement and information systems.

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