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The Dynamics of Diesel-Generator Unit in Isolated Electrical Network

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Abstract-The paper analyses behaviour of diesel-generator units in isolated power system. The aim of this paper is to investigate dynamics due to electrical loads and due to torsional strains on the shaft cable during direct impact load on a such grid. For the purposes of this analyze mathematical model of integral motor drives has been developed. The model includes: a prime mover and speed governor, synchronous generator with voltage control, passive load and induction motor drives. Diesel generator unit is represented as a system with two concentrated masses, synchronous generator rotor and rotating mass of diesel engine, thus the analysis of torsional dynamics during direct-on-line starting of induction motors is allowed. In order to make changes to the loading of an existing isolated electrical grid, it is necessary to analyse and document the effect of the additional loads on its normal and transient performance. This can be achieved by implementing modelling and simulation methods in the designing of power systems.

Keywords- Isolated electrical network, diesel generator-unit, synchronous generator, torsional torque, induction motor starting.

1. Introduction

The demand for energy is increasing globally and, in addition to existing methods of production and conversion, large resources are invested in research into new ways of using energy. In doing so, great attention must be paid to factors of environmental protection, and the process of energy production must be environment friendly. Using renewable energy sources in power systems in the past ten years has increased, particularly in isolated communities that are located away from power grids, or in developing countries with the remote rural areas and at small islands. The availability of renewable sources as wind and solar, strongly contributes to development of power plants. The integration of renewable sources leads to power systems assembled of conventional diesel generating units, electric machines, power electronics converters and batteries, simply: hybrid systems. There are many different concepts for hybrid systems which can consist of any combination of convenient electrical energy sources. Diesel generator is often an element of that system. There are generally two accepted ways of implementing of diesel engine in hybrid energy system configurations:

- Systems based mainly on diesel generators with renewable energy used for reducing fuel consumption.
- Systems based mainly on the renewable energy source with a diesel gen as a backup supply for long periods of low renewable energy input, or during high load period.

Diesel generators are well known for their reliability, relative easy starting, compact power density and portability and as such they are widely applied. But, on the other hand environmental problems with diesel engines are fossil fuel consumption and polluting environment. The first problem can be solved out by replacing fossil fuel with bio-diesel and the second one can be reduced with good construction and minimal used. However, diesel generators are used as the main sources of electricity in cases, such as the ship electrical grid or as backup supplies. In many applications the diesel generator can suffer significant impacts loads that can produce disturbances in the isolated network. However, the autonomous operation of the synchronous generator is characterized by a change in steady state which causes a change in voltage and frequency, which in turn affects the quality of electric power systems.

This rise the problem of correct and precise maintenance planning in order to avoid outages, increase the reliability and to ensure high quality of the electric energy and continuous production along the time. In other case, factory production tests demonstrate the capability of the unit to supply defined loads applied in a defined sequence. In order to make changes to the loading of an existing isolated electrical grid, it is necessary to analyse and document the effect of

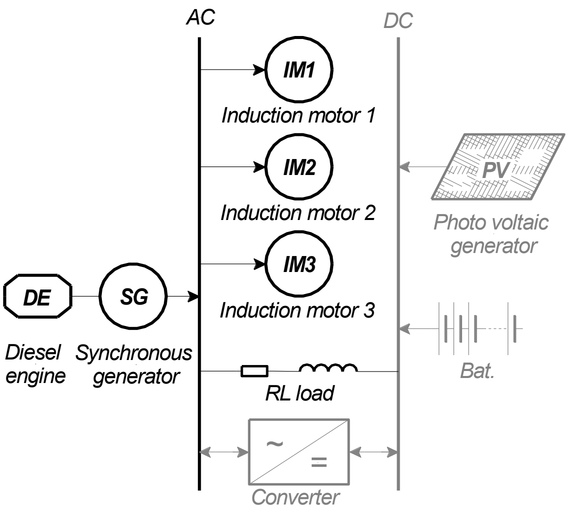


Fig. 1. Scheme of the hybrid system.

the additional loads on its normal and transient performance. This can be achieved by implementing modelling and simulation methods in the designing of power systems. Therefore, it is interesting to analyze the dynamics of a unit with a diesel engine and a synchronous generator.

2. Conception of isolated electrical network

To ensure quality and uninterrupted supply of electricity, it is necessary to predict, remove, or at least to reduce the consequences that may arise in the case of expected or unexpected events such are impact load changes, short circuits, etc. However, implementing modelling and simulation methods will help in solving this [1]. The model considered in this study, analyzes the dynamics of diesel-generator units in isolated electrical network consists of: a diesel engine and a speed controller, a synchronous generator and a voltage controller, a mechanical connection, *RL*- load and three unregulated induction motors fed directly from the synchronous generator terminals (Fig.2).

2.1. Mathematical model of generator-unit

The generator is presented as a machine with three armature windings, field winding and one damper winding D and Q in each axis. Equations are written in generator (source) convention system in which synchronous machines are usually represented [2] and [3], while equation of excitation is written in motor (load) convention system.

A system of voltage equations of the synchronous generator in the rotating *dq* coordinate system, where u, i, r, and ψ denote voltage, current, resistance, and flux, respectively:

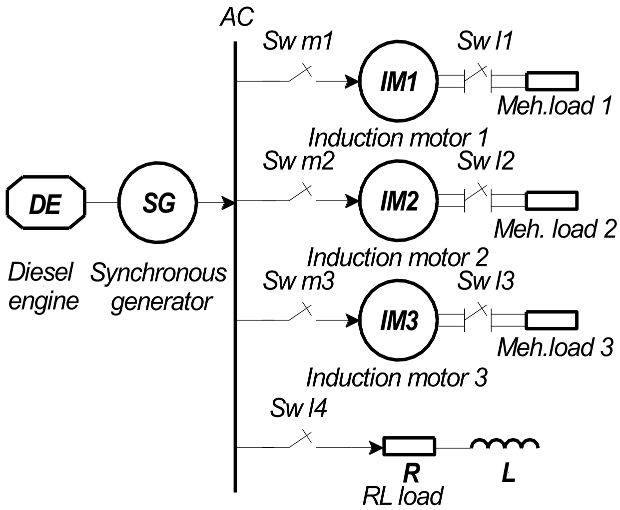


Fig. 2. Conception of isolated electrical network

$$-u_{\mathrm{d}} = r \cdot i_{\mathrm{d}} + \frac{d\psi_{\mathrm{d}}}{dt} - \omega \cdot \psi_q$$
$$-u_{\mathrm{q}} = r \cdot i_{\mathrm{q}} + \frac{d\psi_{\mathrm{q}}}{dt} + \omega \cdot \psi_d$$
$$E_{\mathrm{q}} = e_{\mathrm{q}} + \frac{x_{1d}}{r_1} \cdot \frac{d\psi_1}{dt} \tag{1}$$
$$0 = r_{\mathrm{D}} \cdot i_{\mathrm{D}} + \frac{d\psi_{\mathrm{D}}}{dt}$$
$$0 = r_{\mathrm{Q}} \cdot i_{\mathrm{Q}} + \frac{d\psi_{\mathrm{Q}}}{dt}$$

The voltage controller is modelled as PI and is implemented on the model as described in [4].

The dynamic performance of the diesel engine with its speed control system can be described by the following equations:

$$T_{\mathrm{SC}} \cdot \frac{dT_{\mathrm{DM}}}{dt} = K_{\mathrm{SC}} \cdot \left(e_{\mathrm{ref}} - e_{\mathrm{f}}\right) + K_{\mathrm{SC}} \cdot T_{\mathrm{SC}} \cdot \frac{d\left(e_{\mathrm{ref}} - e_{\mathrm{f}}\right)}{dt} \tag{2}$$

$$T_{\mathrm{f}} \cdot \frac{de_{\mathrm{f}}}{dt} + e_{\mathrm{f}} = K_{\mathrm{f}} \cdot \omega$$

The implemented model of the diesel engine assumes that the engine torque is directly proportional to the fuel consumption. This is allowed when the transients of the synchronous generator are considered.

At the beginning, the whole generator-unit was considered as a single rotating mass and angular velocity is described as:

$$\omega = \frac{1}{J} \int (T_{\mathrm{DM}} - T_{\mathrm{eSG}}) dt \tag{3}$$

where T_{DM} and T_{eSG} denote diesel engine torque and air-gap torque respectively.

The influence of the machine parameters and disturbances on torsional stresses is analyzed in many papers [5, 8]. However, in smaller, isolated electrical grids, it is interesting to analyse the torsional dynamics of a unit, thus, in the second case, mechanical coupling of a diesel engine and a synchronous generator is considered to be a rotating system with two concentrated masses. Masses are connected by flexible coupling. The flexible coupling allows these masses to rotate at a different speed in transients. However, the equations of motion of a generator and for a prime mover are:

$$\frac{d\varphi_1}{dt} = \omega_1, \quad T_{m1} \frac{d\omega_1}{dt} = -T_{\mathrm{eSG}} + C \cdot \Delta\varphi + D \cdot \Delta\omega$$
$$\frac{d\varphi_2}{dt} = \omega_2, \quad T_{m2} \frac{d\omega_2}{dt} = -T_{\mathrm{DM}} + C \cdot \Delta\varphi + D \cdot \Delta\omega \tag{4}$$

where: ω_1, ω_2 , are angular velocity of the generator rotor and prime mover respectively, $\Delta\varphi=\varphi_2-\varphi_1$ - the rotational masses twist angle difference, $\Delta\omega=\omega_2-\omega_1$ - the angle speed difference, T_{m} – mechanical time constant. C is torsional stiffness, and D is the coefficient of internal damping. The variable angle of rotation between them occurs, allowing thus the analysis of the torsional dynamics in the coupling.

The torque at coupling zone between two concentrated rotational masses is:

$$T_{\mathrm{t}} = C \cdot \left(\varphi_2 - \varphi_1\right) \tag{5}$$

2.2 Mathematical model of passive and active load

Three phase symmetric load is modeled as system of voltage equations in *dq* axes form, where the resistance R_{l} and reactance x_{l} refer to the passive consumers:

$$u_{\mathrm{dl}} = R_{\mathrm{l}} \cdot i_{\mathrm{dl}} + x_{\mathrm{l}} \frac{di_{\mathrm{dl}}}{dt} - \omega \cdot x_{\mathrm{l}} \cdot i_{\mathrm{ql}}$$
$$u_{\mathrm{ql}} = R_{\mathrm{l}} \cdot i_{\mathrm{ql}} + x_{\mathrm{l}} \frac{di_{\mathrm{ql}}}{dt} + \omega \cdot x_{\mathrm{l}} \cdot i_{\mathrm{dl}} \tag{6}$$

The standard mathematical model of the induction motor [2, 9] with two stator's and rotor's voltage equations is implemented: where u, i, R, and ψ denote voltage, current, resistance and flux of an induction motor respectively. As one can differentiate variables of induction motor and synchronous generator index A is used in Eq.(7):

In the transient *dq* axis model of a synchronous generator, as well as in induction motors model, all winding currents are selected as state variables. The model is completed with an equation of the rotational mass motion, where: T_{eIMn} denote air-gap torque of the induction motor and T_{Ln} represents load torque on the motor's shaft:

$$\begin{aligned} u_{\mathrm{dAn}} &= R_{\mathrm{sn}} i_{\mathrm{dAn}} + \frac{d\psi_{\mathrm{dAn}}}{dt} - \omega \cdot \psi_{\mathrm{qAn}} \\ u_{\mathrm{qAn}} &= R_{\mathrm{sn}} i_{\mathrm{qAn}} + \frac{d\psi_{\mathrm{qAn}}}{dt} + \omega \cdot \psi_{\mathrm{dAn}} \\ 0 &= R_{\mathrm{rn}} i_{\mathrm{DAn}} + \frac{d\psi_{\mathrm{DAn}}}{dt} - (\omega - \omega_{\mathrm{An}}) \cdot \psi_{\mathrm{QAn}} \\ 0 &= R_{\mathrm{rn}} i_{\mathrm{QAn}} + \frac{d\psi_{\mathrm{QAn}}}{dt} + (\omega - \omega_{\mathrm{An}}) \cdot \psi_{\mathrm{DAn}} \end{aligned} \tag{7}$$

All variables and parameters are in per unit

$$T_{\mathrm{mIMn}} \cdot \frac{ds_{\mathrm{n}}}{dt} = T_{\mathrm{Ln}} - T_{\mathrm{eIMn}} \tag{8}$$

(p.u.). Index n denotes the motor implemented in the model, thus it can be equal to 1, 2 and 3 for the first, the second and the third induction motor, respectively. When the induction motor starts unloaded, then the torque T_{Ln} equals zero. Also, for this analysis the loading with a constant load of $T_{\mathrm{Ln}}= 0.05$ p.u. was selected.

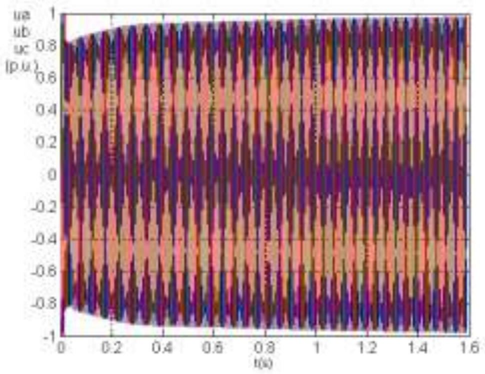
Loads are connected directly to a synchronous generator, what means that they are on the same voltage as the generator terminals: $-u_{\mathrm{d}} = u_{\mathrm{d}\ell}$, $-u_{\mathrm{q}} = u_{\mathrm{q}\ell}$ in a case of *RL*- load and $-u_{\mathrm{d}} = u_{\mathrm{dA1}} = u_{\mathrm{dA2}} = u_{\mathrm{dA3}}$, $-u_{\mathrm{q}} = u_{\mathrm{qA1}} = u_{\mathrm{qA2}} = u_{\mathrm{dA3}}$ for synchronous generator and induction motors. According to the Kirchhoff's law, the current relationship between supplying and receiving elements can be expressed for *RL*- load as: $i_{\mathrm{d}} = i_{\mathrm{d}\ell}$, $i_{\mathrm{q}} = i_{\mathrm{q}\ell}$ and for synchronous generator and induction motors: $i_{\mathrm{d}} = i_{\mathrm{dA1}} + i_{\mathrm{dA2}} + u_{\mathrm{dA3}}$, $i_{\mathrm{q}} = i_{\mathrm{qA1}} + i_{\mathrm{qA2}} + i_{\mathrm{qA3}}$.

3. Study Cases and Computation Results

The analysis was performed by the application of program package "Matlab/Simulink". The validity of the mathematical model of the generator-unit at impact load–direct-on-line starting of non-loaded induction motor was checked in the previous work [9], [10] by comparing the results of the simulation and the measurement on the generator-unit with a diesel engine of *46.4* kW and a synchronous generator of *40* kVA, to which a motor drive of *7.5* kW was connected (Nominal data are in Appendix).

The synchronous generator is initially in a steady state unloaded condition operating at the rated voltage (*1* p.u.) and stator currents being zero. The rotation speed of the diesel generator-unit (ω) is equal to the rated speed of *1* p.u. In the first case the *RL*- load (Z=*1*∠arcos*0.8*) is connected directly to the terminals of the synchronous generator and voltage and current transient are presented in Fig.3. As one can see, impact load causes the voltage drop; the current is increased and reaches *1* p.u.

The connection of induction motor to the isolated electrical grid is the most difficult transition regime for the units. This causes voltage



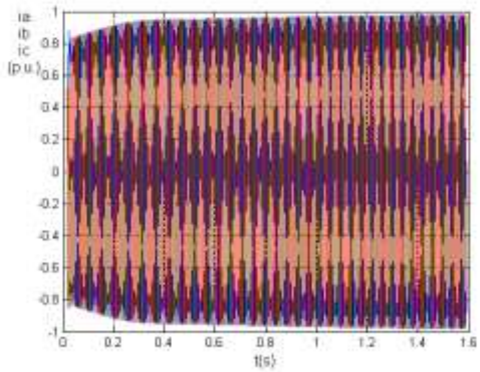


Fig. 3. Voltage and current of synchronous generator during impact *RL*- load.

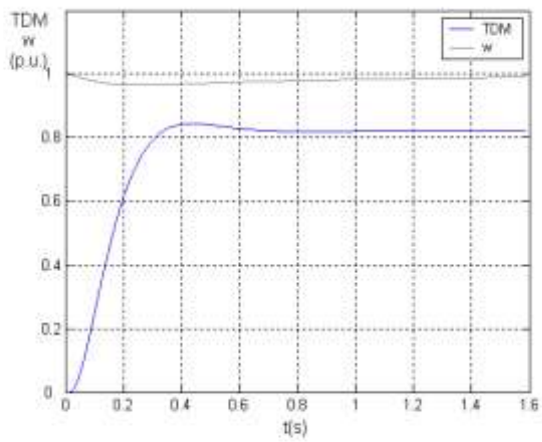


Fig. 4. Speed transient of diesel-generator unit (ω) and diesel engine torque (T_{DM}) during impact *RL*- load.

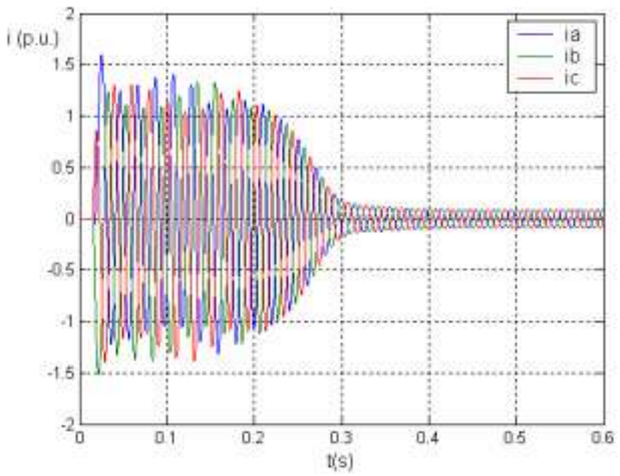


Fig. 5. Current of synchronous generator During direct on line starting of induction motor.

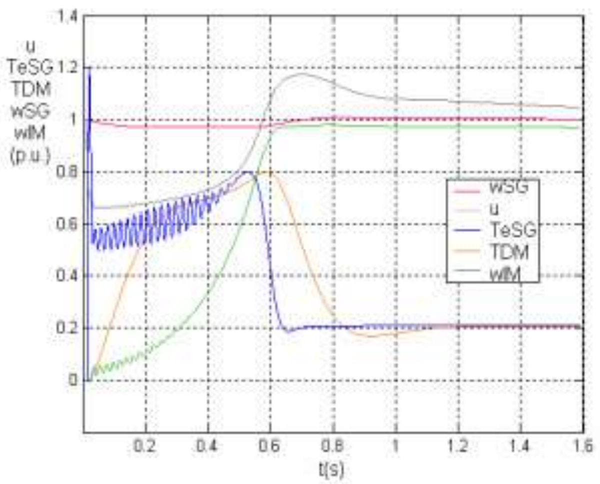


Fig. 6. Transient of air-gap torque (T_{eSG}) and diesel engine torque (T_{DM}), voltage and speed transent of transient of diesel-generator unit (ω_{SG}) and induction motor.

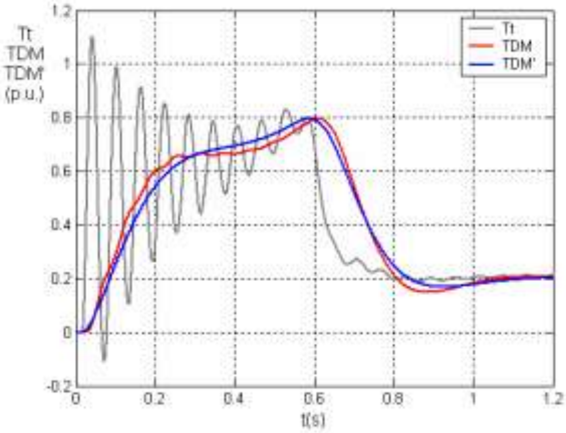


Fig. 7. Transient of diesel engine torque T_{DM} (one mass) and T'_{DM} (two masses); torsional torque T_t.

reductions at the generator terminals as well as speed reductions during motor starting. Start up current of induction motor multiple exceeds rated current (Fig. 5). As one can see (Fig.4 and Fig.6) at the beginning of the impact load the speed of diesel motor is decreased in both cases, because the speed regulator does not act jet. Action speed regulator increases the flow of fuel diesel engine, increasing torque and engine speed. In these cases the whole diesel-generator unit was considered as a single rotating mass. When the induction motor is connected, the load on the unit is instantaneously increased and electromagnetic torque of the synchronous generator reaches momentarily the maximum value (*1.20* p.u.). Oscillations are continuing during the whole start-up period and are damped at the end of run-up period of induction motor (Fig.6). Also, torsional strains appear in the shaft line.

However, in the second case the mechanical system of the motor generator set is modelled as a rotating system with two concentrated masses a diesel motor rotor and a synchronous generator rotor. These two masses are connected by flexible coupling. In this way, masses rotate at different speeds in the transients (Fig.7). It is allowed to analysis of the torsional dynamics in the coupling (Fig.8).

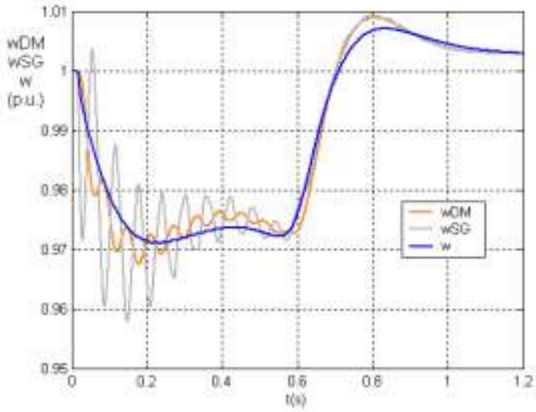
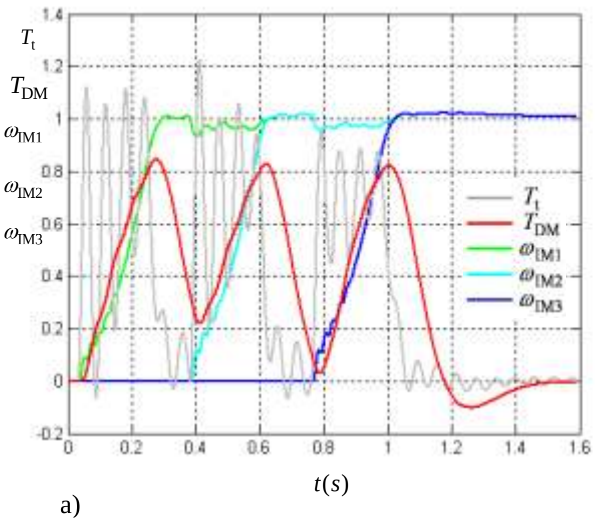
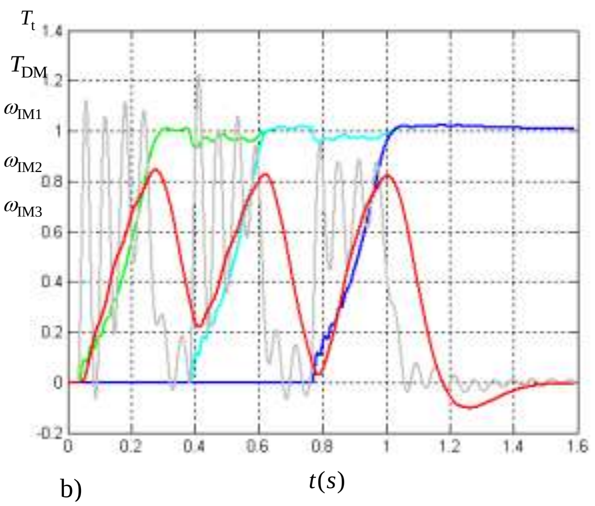


Fig. 8. Speed transient of the synchronous generator (ω_{SG}) and diesel motor (ω_{DM}),during start-up period of IM1, IM2 and IM3 speed transient ω (one mass).



a)



b)

Fig. 9. Transients of: torsional torque (T_t) and diesel engine torque (T_{DM}), speed transient of the induction motors (ω_{IM1}, ω_{IM2}, ω_{IM3});
a) $T_{lIM1}=T_{lIM2}=T_{lIM3}=0$, b) $T_{lIM1}=T_{lIM2}=T_{lIM3}=0.05$p.u.

In the next step, the model is extended with few active consumers. Here, three induction motors are connected on diesel generator unit. Direct starting of induction motors in isolated electrical networks causes a significant disturbance in transients, especially if the load torque on the motor shaft is increased

At the chosen moment, the first unloaded, induction motor (IM1) is connected directly to the terminals of the synchronous generator. Later, when the first motor has run up successfully, the second (IM2) and the third (IM3) unloaded induction motor are connected to the loaded synchronous generator (Fig. 9a).

In the other case, as one can see in Fig.9b, motors are loaded with a constant load $T_{lIM1}=T_{lIM2}=T_{lIM3}=0.05$ p.u. and after the first motor has run-up successfully, the second (IM2) and third (IM3) loaded induction motors are connected to the grid. When the supply has just been switched on the induction motor, the load on the generator-unit is instantaneously increased; the torque of diesel engine is growing up and reaches max. value at the end of the start up period of the induction motor (Fig.9).

In small electrical network most induction motors are direct-on-line switch-started (as on board ship) and they cause a significant disturbance in transients, especially if the load torque on the motor shaft is increased and also depending on the time of the starting of each motor. It is a particularly difficult situation because of relatively strong electrical coupling between generator and loads as well as torsional strains in the shaft line. In order to get a better insight into the dynamics of drives, as one can see in Fig.10 the second induction motor (IM2) has been connected to the supply during the start up period of the first one (IM1), while the next induction motor (IM3) has been connected during the start up period of the previous one.

The prime mover torque (T_{DM}), at the beginning of the start up period of the IM2, reaches *1* p.u., increases, and at the beginning of the start up period of the IM3 reaches maximal value of *1.16* p.u. Finally it should be noted that the max. prima mover torque noted that the max. prima mover torque is larger if the third motor (IM3) is switched on the supply at the end of the start-up period of the second one (Fig.10), however in that case it reaches *1.02* p.u.

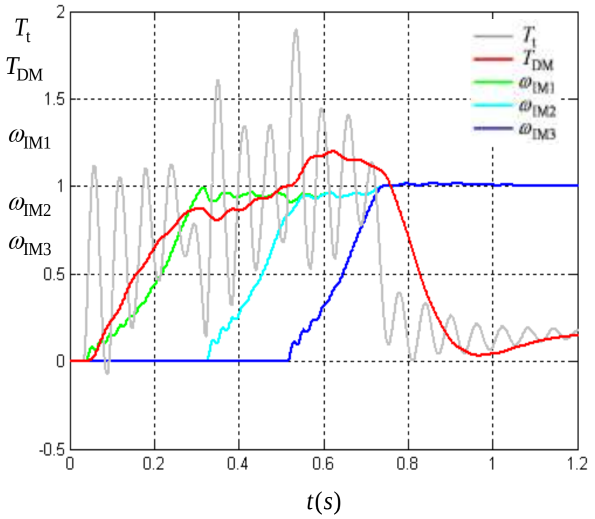


Fig. 10. Transient of: diesel engine torque (T_{DM}), speed transient of the induction motors (ω_{IM1}, ω_{IM2}, ω_{IM3}) and torsional torque (T_t), during start-up period of loaded IM1, IM2 and IM3. the next motor is started at the end of start up period of previous one.

When the induction motor is connected, the load on the unit is instantaneously increased, defined in the initial (sub-transient) phase of the transitional locked-rotor torque of the induction phenomenon by locked-rotor torque of the induction motor. The synchronous generator T_{eSG}, as well as change in the electromagnetic torque of the electromagnetic torque of induction motors (T_{eIM}) are presented in Fig.12.

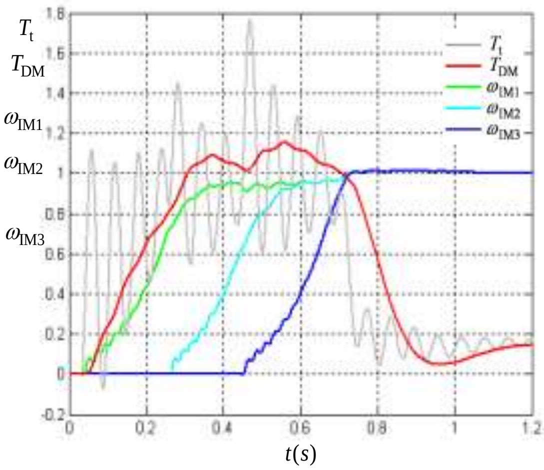


Fig. 11. Transient of: diesel engine torque (T_{DM}),speed transient of the induction motors (ω_{IM1}, ω_{IM2}, ω_{IM3}) and torsional torque (T_t), during start-up period of loaded IM1, IM2 and IM3. the next motor is started at the beginning of start up period of previous one

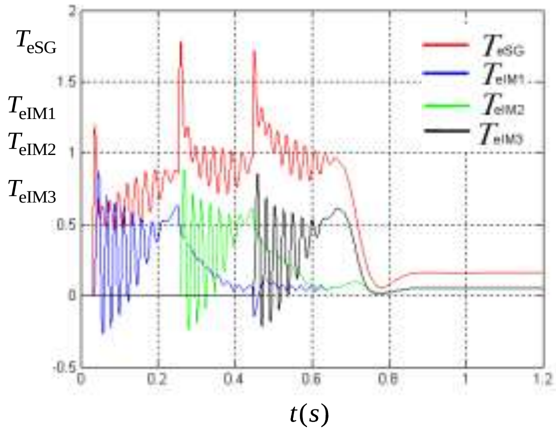


Fig. 12. Transient of the air-gap torque of the synchronous generator (*T*eSG) and induction motors (*T*eIM1, *T*eIM2, *T*eIM3) for the case described in Fig.10.

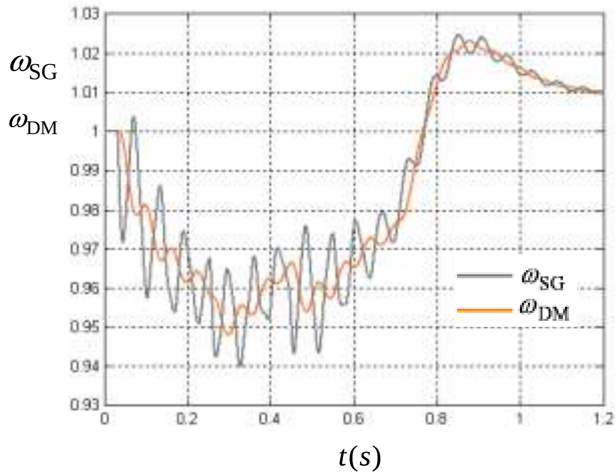


Fig. 13. Speed transient of the synchronous generator (ω_{SG}) and diesel motor (ω_{DM}), during start-up period of IM1, IM2 and IM3 for the case described in Fig.10.

Changes in the air-gap torque (T_{eSG}) can be noticed during the whole start-up period of induction motors. This results in the difference of the torque angle between the generator rotor and the diesel engine shaft due to the definite final stiffness of the shaft and different inertia of generator and diesel engine, however, torque in the coupling T_t (Fig. 9, Fig.10 and Fig.11). The oscillations in torsional torque are longer present and, as can be noticed, damped at the end of the starting period of the induction motors. The oscillations are present in speed transients of the synchronous generator (ω_{SG}) as well as in diesel engine (ω_{DM}) (Fig. 13).

4. Conclusion

Behaviour of diesel-generator units in isolated power system is interesting, especially in case of direct on line starting of induction motors. It is the most difficult case of impact loads both in terms of electrical loads and stresses due to shaft torsion. They cause a significant disturbance in transients, especially if the load torque on the motor shaft is increased and also in the cases of the starting of the next induction motor while the previous motor starting is not yet finished. However, this will have an impact on the developed engine torque, and accordingly, the increased fuel consumption.

Accordingly, it may be concluded that the developed mathematical model of integral motor drives as well as results obtained by this analysis enables to avoid starting and connecting of significant loads on isolated electrical grid in certain moment, if there are any. However it can be used as a guideline in choosing and setting parameters of the protection devices.

Acknowledgements

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Appendix

Synchronous generator: 40 kVA, 3x400/231 V, cos φ=0.8; 57.7 A;1500 r/min; 50 Hz

$x_d = 2.5$; $x_q = 1.6$; $x_d^{'} = 0.32$; $x_d^{''} = 0.129$; $x_q^{''} = 129$;

$x_1 = 0.071$; $r_a = 0.0266$ (in *p.u.*)

$T_d^{'} = 0.2$ s; $T_d^{''} = 0.0034$ s; $T_q^{''} = 0.0034$ s

J=0.501 kgm^2; $T_m = 2$ s.

Diesel motor: 46.4 kW, 1500 r/min

Induction motors: Δ 380 V, 14,7 A, 7,5 kW, 2905 r/min, cos φ=0.9.

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