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The Dynamics of Induction Motor Fed Directly from the Isolated Electrical Grid

Marija Mirošević

Additional information is available at the end of the chapter

1. Introduction

An induction motor is the most common machine used for industrial drives. It is used in variety of drives due to its robust construction, relatively low cost and reliability. In isolated electrical network, such as marine and offshore power systems and emergency generation plant, induction motors are the most power consuming loads and are used for winches, water pumps, compressors, fans and for other on-board applications, in continuous mode or intermittently.

In many applications induction motors are direct-on-line switch-started. Their dynamic characteristics have an obvious influence on the transient process of power system; however, they cause a significant disturbance in transients (significant impacts loads) that can produce disturbances in the isolated electrical network, which in turn affects the quality of electric power system and thus, on the dynamic behavior of induction motors.

Direct-on-line starting represents the simplest and the most economical system to start squirrel-cage induction motor. During starting induction motors draw high starting currents which are several times the normal full load current of the motor. This current causes a significant voltage dip on the isolated electrical grid until the induction motors reach nearly full speed. This voltage drop will cause disturbances in the torque of any other motor running on the isolated electrical grid. Significant disturbances in transients are caused by direct-on-line switch-started induction motors, especially if the load torque on the motor shaft is increased and beside that, also by the sudden change load, such as the impact load on the motor shaft (McElveen, et al., 2001; Cohen, 1995). This situation is particularly difficult because of relatively strong electrical coupling between electrical grid and loads. Besides the voltage dips, an interruption can also appear, which further affects on the fatigue of induction motors connected to the grid. When an interruption of the supply lasts longer than one voltage period, many AC contactors will switch off the motor. In some

cases, faulty contactor may produce multiple switching on and off. However, these interruptions will affect the dynamics of both electrical and mechanical variables. Therefore, it is interesting to analyze dynamics of the induction motor in case when it comes to short-term interruptions in the motor power supply.

That's why the dynamic behavior of induction motors fed directly from isolated electrical grid, as well as dynamics of aggregate is in focus of researchers. Presently, advanced modeling and digital simulation techniques can be used to analyse the dynamics behavior of electrical as well as mechanical systems.

2. Mathematical models used in isolated electrical grid

The aim is to analyze the dynamics of the induction motors fed directly from the isolated electrical grid. For this purposes the mathematical model of isolated electrical grid has been develop consisting diesel electrical aggregate and unregulated induction motors.

Diesel generators are used as the main sources of electricity in cases of isolated systems. In many applications the diesel generator can suffer significant impacts loads that can produce disturbances in the isolated grid. 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.

The model of diesel electrical aggregate considered in this study consists of: a diesel engine and a speed controller, a synchronous generator and a voltage controller, a mechanical connection between engine and electrical machine shaft.

The synchronous generator is presented as a machine with three armature windings, a magnetizing winding on the rotor and damper windings. One damper winding is located along direct-axis (D), and one along the quadrature-axis (Q). The basis of the mathematical model is a set of differential equations of the synchronous generator in the standard dq-axis form (Kundur, 1994). The voltage equations are written in generator (source) convention system, in which synchronous machines are usually represented:

$$-u_d = r \cdot i_d + \frac{d\psi_d}{dt} - \omega \cdot \psi_q \tag{1}$$

$$-u_q = r \cdot i_q + \frac{d\psi_q}{dt} + \omega \cdot \psi_d \tag{2}$$

$$E_q = e_q + \frac{x_{1d}}{r_1} \cdot \frac{d\psi_1}{dt} \tag{3}$$

$$0 = r_D \cdot i_D + \frac{d\psi_D}{dt} \tag{4}$$

$$0 = r_Q \cdot i_Q + \frac{d\psi_Q}{dt} \tag{5}$$

where *u*, *i*, *r*, and *ψ* denote voltage, current, resistance and flux respectively.

The model of a synchronous generator is given in rotor reference frame (ω is rotor electrical speed). The equations of excitation in motor (load) convention system are written. The voltage controller, modeled as PI, is implemented in the model of the synchronous generator.

The model of the prime mover - the diesel engine assumes that the engine torque is directly proportional to the fuel consumption. In order to describe the dynamic behavior of the diesel engine it is necessary to set up a system of differential equations which includes an equation of the engine, the turbocharger, the air collector, the exhaust system, and the speed controller. Taking into account these equations requires the knowledge of characteristics of diesel engines that require complex experimental measurements, according to (Krutov, 1978; Tolšin 1977). The studies carried out in (Erceg & et al. 1996) showed that the mentioned omissions do not affect significantly the results and that the proportionality of torque to the amount of injected fuel can be assumed. This simplification is allowed when it is of interest to observe dynamics of a synchronous generator as well as induction motors. The speed controller is modeled as PI and implemented in the model.

Sudden impact load on the diesel electrical aggregate is the most difficult transition regime for units due to electricity loads and also due to torsional strains in the shaft lines. A more significant disturbance, which is at the same time very common in practice, is the direct-on-line starting of induction motors to such a grid. Starting of induction motors will cause voltage dips and will reduce engine speed depending on the time of the starting of each motor. This will also cause torsional stresses in the shaft. Thus, the 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.

The variable angle of rotation between these masses occurs during the transient, in period when mechanical balance between diesel engine and electric generator is disturbed., The torque which appears at coupling zone between two concentrated rotational masses allows thus the analysis of the torsional dynamics in the coupling.

Induction motor as an active consumer and its parameters were analyzed in (Maljkovic, 2001; Amezquita-Brook et al., 2009). According to (Jones, 1967; Kraus 1986) three phase squirrel-cage induction motors are represented with stators and rotors voltage equations:

$$u_{dIM} = R_{sIM} \cdot i_{dIM} + \frac{d\psi_{dIM}}{dt} - \omega \cdot \psi_{qIM} \tag{6}$$

$$u_{qIM} = R_s \cdot i_{qIM} + \frac{d\psi_{qIM}}{dt} + \omega \cdot \psi_{dIM} \tag{7}$$

$$0 = R_r \cdot i_{DIM} + \frac{d\psi_{DIM}}{dt} - \left(\omega - \omega_{IM}\right) \cdot \psi_{QIM} \tag{8}$$

$$0 = R_r \cdot i_{QIM} + \frac{d\psi_{QIM}}{dt} + \left(\omega - \omega_{IM}\right) \cdot \psi_{DIM} \tag{9}$$

where: u, i, R, and ψ denote voltage, current, resistance and flux respectively of an induction motor.

All winding currents, in the transient dq axis model of induction motors as well as in a synchronous generator model, are selected as state variables. The model is completed with an equation of the rotational mass motion (Vas, 1996). All variables and parameters are in per unit (p.u.). The motor's equation of motion involves electrical torque (T_{eIM}), whereas (T_{lIM}) represents load torque on the motor's shaft.

When the induction motor starts unloaded, then the torque T_{lIMn} equals zero. Also, for this analysis the loading with a constant load was selected.

Loads, induction motors (index IM), are connected directly to a synchronous generator (index SG), what means that they are on the same voltage as the generator terminals: $-u_d=u_{dIM1}=u_{dIM2}$, $-u_q=u_{qIM1}=u_{qIM2}$. According to the Kirchhoff's law, the current relationship between supplying and receiving elements are: $i_d=i_{dIM1}+i_{dIM2}$, $i_q=i_{qIM1}+i_{qIM2}$.

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 (Mirosevic, et al. 2002a, 2011b) by comparing the results of the simulation and the measurement on the generator-unit with a diesel engine of 46.4 kW, 1500 r/min and a synchronous generator of 40 kVA (3x400/231 V, cos φ=0.8; 57.7 A; 1500 r/min; 50 Hz), to which a motor drive of 7.5 kW (Δ 380 V, 14.7 A, 2905 r/min, cos φ=0.9) was connected. The results obtained by numerical calculation indicate that, the set mathematical model can be applied with sufficient certainty

The analysis of the dynamics of induction motors fed directly from the isolated electrical grid was performed by the application of program package "Matlab/Simulink". The block diagram of integral motor drives is presented in Figure 1 involves: a diesel engine (DM, SC), a three phase synchronous generator and voltage controller, their mechanical coupling and induction motors fed directly from the synchronous generator terminals.

Block diagram of Diesel engine and speed controller is presented in Figure 2 and represents subsystem of block naimed as DM SC in Fig. 1.

The Simulink is used to obtain a model of a diesel generator unit, as well as induction motors by means of basic function blocks that can be linked and edited to subsystem such as subsystems IM 1 and IM 2 in Figure 1 which representthe first and the second induction motors respectively. As one can see in Figure 3 components of the subsystem IM 1 that are used in the calculation of variables are presented.

Induction motors are connected to the network using power supply subsystem, while the load on the motor shaft is represented with subsystems: load IM1 and load IM2 in Figure 1.

Moment of switching/disconnecting on the network is controlled by means of the subsystem ON/OFF, also, the part of this subsystem is used to set the time of switching/disconnecting the load on the motor shaft.

All calculations were carried out by means of the "Variable-Step Kutta-Merson" method – an explicit method of the fourth order for solving the systems of differential equations, with variable integration increment.
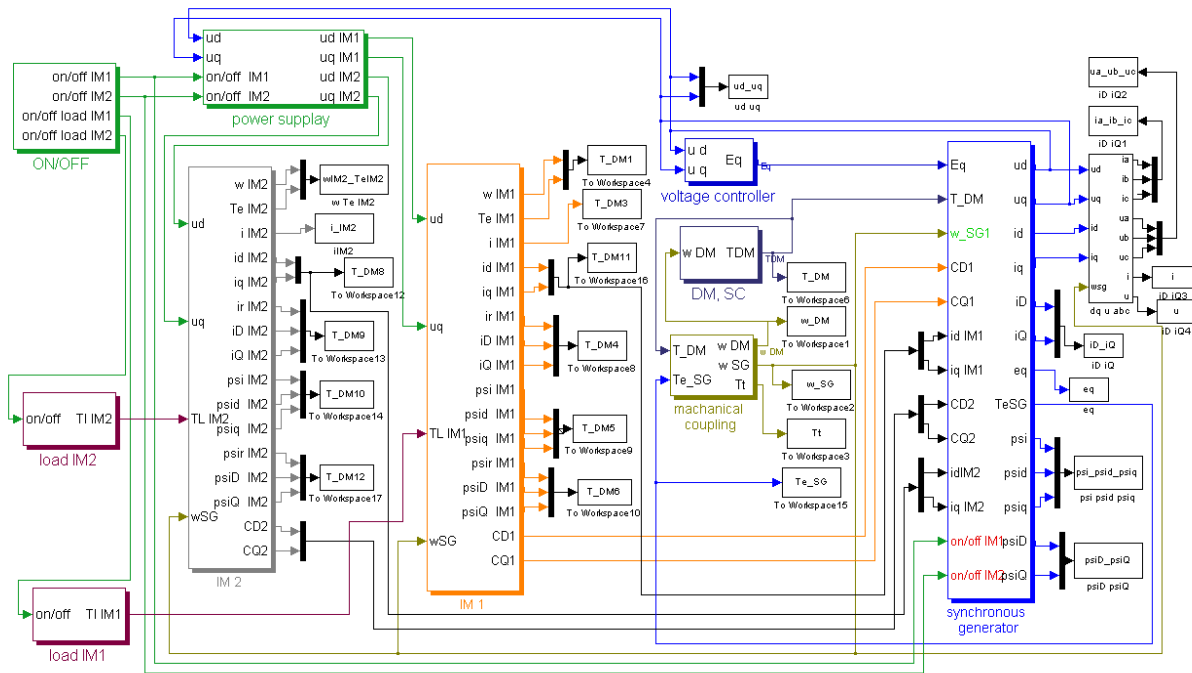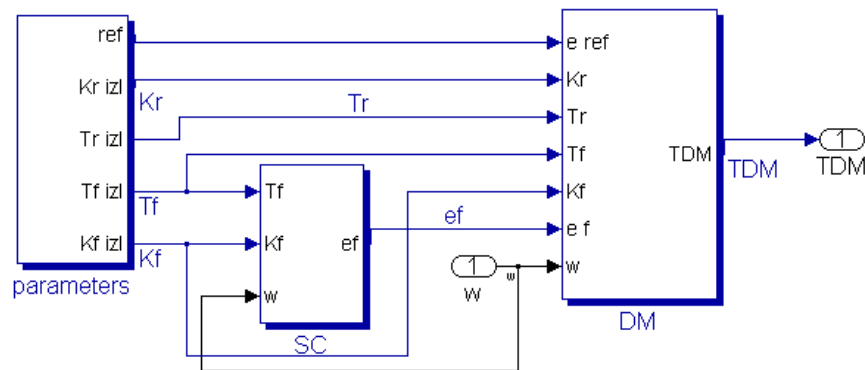

Figure 1. Simulation of the applied mathematical model

Figure 2. Diesel engine and speed controller model
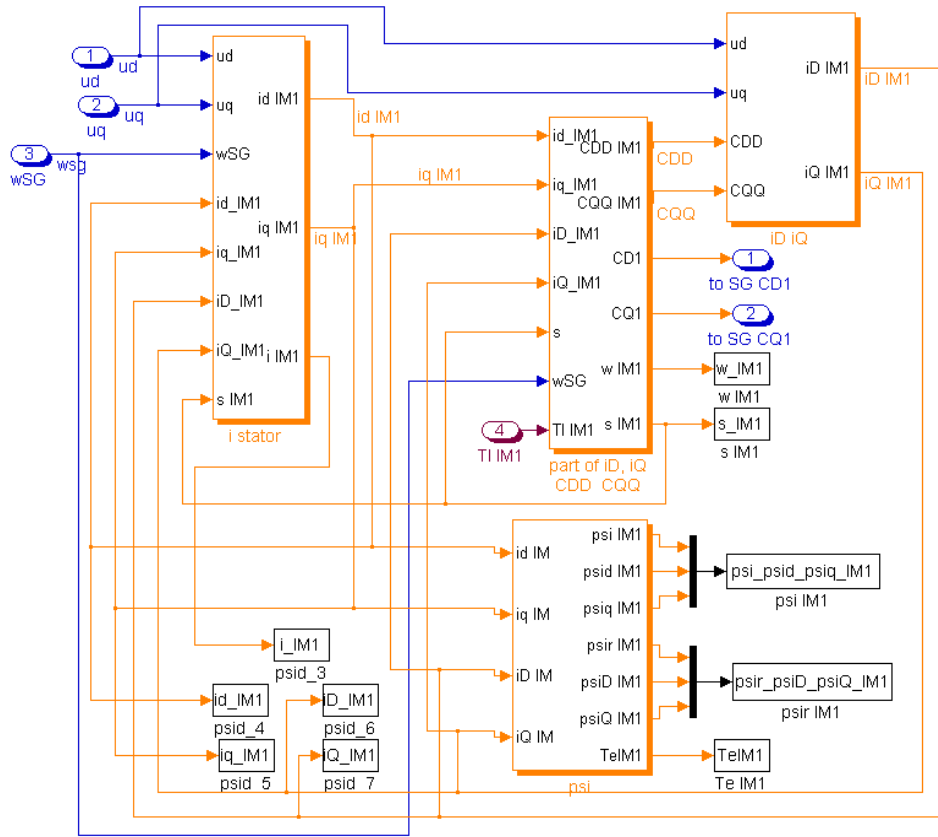
Figure 3. Induction motor model

3. Induction motor starting

At the beginning, two induction motors are connected directly to an isolated electrical grid. The first induction motor (IM1) is connected to the terminals of the aggregate and later, when the first motor has run-up successfully, the second induction motor (IM2) is connected to the grid.

The synchronous generator is initially in a steady state unloaded condition. However, in this condition stator current is zero, rated voltage is on its terminals, while rotation speed of the diesel engine (ω_{DM}) is equal to the speed of the generator (ω_{SG}) and is equal to 1 p.u.

The first observed dynamics is for the case of the starting of unloaded induction motors and in the second case dynamics of loaded induction motors are considered. Transients of: air-gap torque and speed transient of induction motors, terminal voltage, speed transient of synchronous generator and diesel engine, for both cases are presented in Figure 4.

Initially, the first induction motor is starting from rest, the rated voltage is applied on its terminals and there is no mechanical load on the motor shaft. When the induction motor is connected, the load on the aggregate is instantaneously increased, defined in the initial (sub-transient) phase of the transitional phenomenon by locked-rotor torque of the induction motor. As the motor accelerates, its torque grows and the generator load rises. When

maximum torque is achieved, the load of the synchronous generator reaches its maximum and then decreases rapidly.

At the instant of starting, as one can see in Fig. 4a, the air-gap torque is momentarily increased; reaches maximum value of 0.86 p.u. and change in it can be noticed during the whole start-up period of the first induction motor. The instantaneous torque oscillates about positive average value.
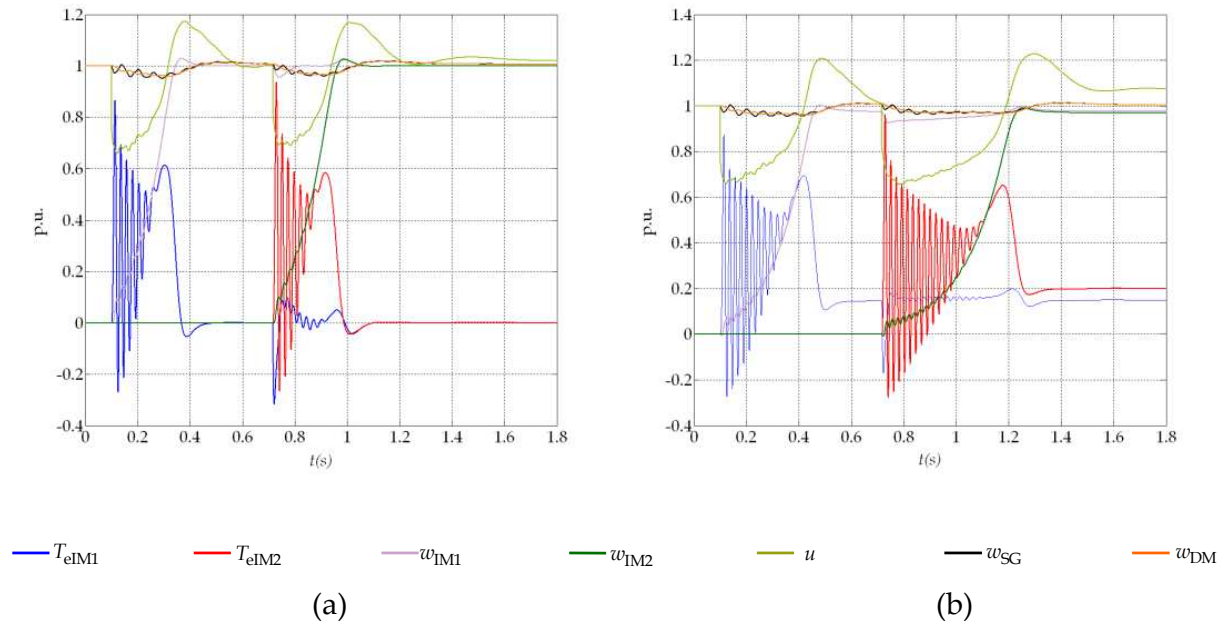

Figure 4. Transients of: air-gap torque of induction motors (T_{eIM1}, T_{eIM2}) and speed transient of induction motors (ω_{IM1}, ω_{IM2}); terminal voltage (u), speed transient of synchronous generator (ω_{SG}) and diesel engine (ω_{DM}), during direct-on-line starting of: a) unloaded b) loaded induction motors

The oscillations in the air-gap torque are caused by the interactions between the stator and rotor flux linkage. The negative oscillations in the electromagnetic torque of the induction motor are presented at the beginning of the start-up period. These are periods of momentary deceleration that occur during regeneration when the electromagnetic torque becomes negative. The rotor speed only increases when the torque is positive. The oscillations that are present in transient of air-gap torque of the first induction motor are damped at the end of start up period and finally the steady state condition is attained without oscillations.

The response of the air-gap torque is in accordance with the response of the motor currents. Transients of stator currents of induction motors and their components, for both cases, are presented in Figure 5.

Under this condition the starting current is large. The starting current of an induction motor is several times larger than the rated current since the back emf induced by Faraday's law grows smaller as the rotor speed increases. However, a large starting current tend to cause the supply voltage to dip during start-up and can cause problems for the other equipment that is connected to the same grid.
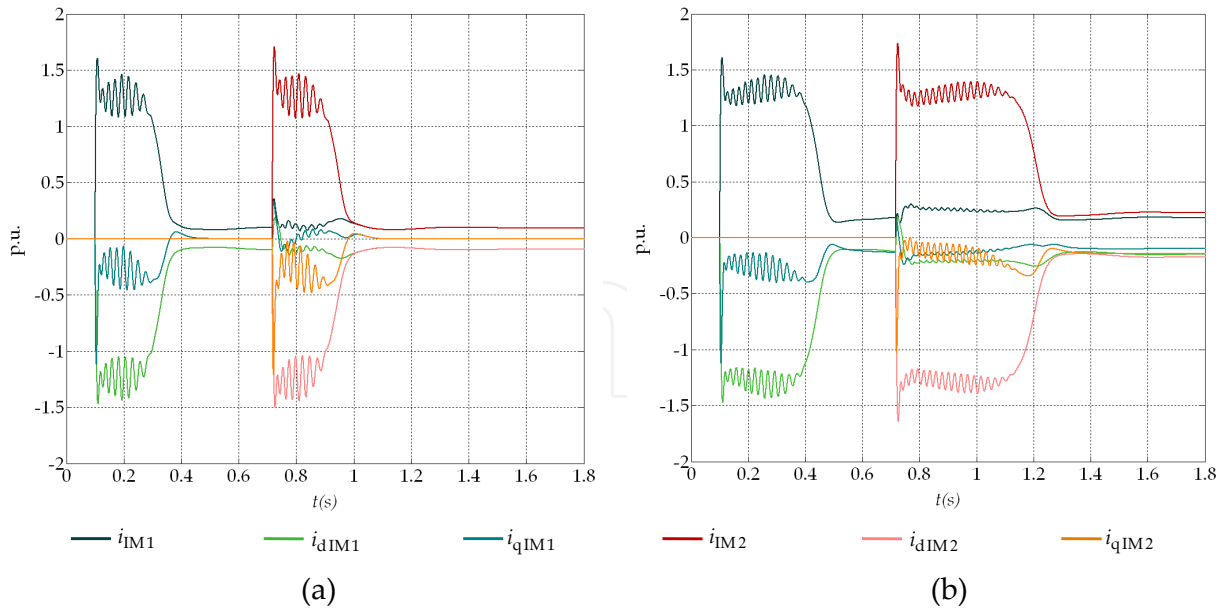
Figure 5. Transients of stator currents of induction motors (i_{IM1}, i_{IM2}) and their components in d (i_{dIM1}, i_{dIM2}) and q (i_{qIM1}, i_{qIM2}) axis during direct-on-line starting of: a) unloaded b) loaded induction motors

At the instant of starting, when the supply has just been switched on the induction motor, the first magnitude of starting current momentarily reaches maximum value of 1.61 p.u. as it is presented in Fig. 5a. The damped oscillations, that are present in stator current transients, disappear at the end of the starting period of the induction motors. When the first motor has run-up successfully, the second induction motor (IM2) is connected to the loaded synchronous generator. Involvement of the second induction motor to the isolated electrical grid the network load instantaneously increased and voltage drop occurs.

The terminal voltage is momentary decreased (Fig. 4a) and after few damped oscillations reached minimal value. However, the high starting currents are appeared. High inrush current, in the first moments, as one can see in Figure 5, reaches the magnitude of the first oscillation of 1.73 p.u. The air-gap torque of the second induction motor T_{eIM2} momentarily achieves 0.94 p.u.

At the moment of switching on to the grid, the second induction motor begins to accelerate and oscillations are present in its transients of air-gap torque during the acceleration period. At the time of the starting of second induction motor (IM2), the reverse torque impulse of 0.31 p.u. in air-gap torque of the first one (IM1) is appeared but decayed rapidly. As the torque of the first induction motor becomes negative motor speed slows down. Thereafter, damped oscillations that are present in the response of electromagnetic torque of the first motor as well as oscillations in electromagnetic torque of the second one are stifled at the end of the run-up period of the second induction motor.

At the beginning of the start-up period of the second motor, the speed of the first one decreases and afterwards recovers. Overshoot in the speed transient occurs at the end of start-up period of the second induction motor.

The starting of loaded induction motor is more difficult transition regime for the aggregate, therefore, the transients of aggregate are slower.

Thus, in the second case, the dynamics of the starting of loaded induction motors is analyzed, however, the load on the first one is T_{lIM1}=0.15 p.u. while T_{lIM2}=0.2 p.u. is applied on the second one. In this case the acceleration time is longer than in the previous case when motors are started unloaded (Fig. 4a), the voltage of synchronous generator is recovering slower, and will be lower then 80%U_n during greater part of start up period, as presented in Fig. 4b.

The initial part of the transients of electromagnetic torque is equal in both cases (load and non-load condition). At the time of the starting of the first induction motor the torque T_{eIM1} reaches a value of 0.86 (p.u.).

At the instant of connection to power supply the instantaneous torque is independent of the balanced source voltages because the machine is symmetrical, even air-gap torque depends upon the values of source voltages though the stator currents. In addition, the air-gap torque oscillates with higher magnitude, about lower average then in case of unloaded motor. These oscillations are damped at the end of the start-up period of the induction motor as presented in Figure 4b.

The component of air-gap torque, which appears because of mutual acting of free currents in stator as well as in rotor windings acts as counter torque on motors shaft and disappears before the end of the run-up. As one can see in Fig 4 the duration of the start-up of both induction motors is longer than in the previous case, in which the motors run-up unloaded. Thus, this acceleration period of second induction motor is 500 ms, while in the previous case lasted 230 ms. In Fig. 5b stator currents, in *dq* axis, and their components, during start up of loaded induction motor, are presented. As the induction motor is directly connected to the terminals of unloaded synchronous generator that means that stator current of induction motor is at the same time the armature current of synchronous generator.

At the beginning of the transient phenomena inrush current which appears during the first half period is dominating but disappears quickly. After initial damping, oscillations of free currents will continue with slightly greater magnitude than at the beginning of transients. These currents, which also can be seen during the start up period of unloaded induction motor, disappear at the end of start up. Corresponding stator flux linkage, during direct-on-line starting of unloaded and loaded induction motor are presented in Fig. 6.

The transients of the first induction motor current in *abc* coordinate system (i_{abcIM1}), in both cases, are presented in Fig. 7. The current of synchronous generator (i_{abcSG}), in both cases, is presented in Fig. 8. This is the total current that motors draw from the electrical grid.

The phenomena of voltage and frequency deviation are typical for isolated electrical grid which in turn affects the quality of electric power systems. The short-term frequency deviation, during direct-on-line starting unloaded and loaded induction motors are presented in Figure 9. There is relatively strong electrical coupling between synchronous

generator and loads as well as torsional strains in the shaft line. However, the torque in the coupling for both cases is presented in Figure 10. Oscillations in transients of torsion torque are longer present during direct-on-line starting loaded induction motor and damped at the end of start-up period.
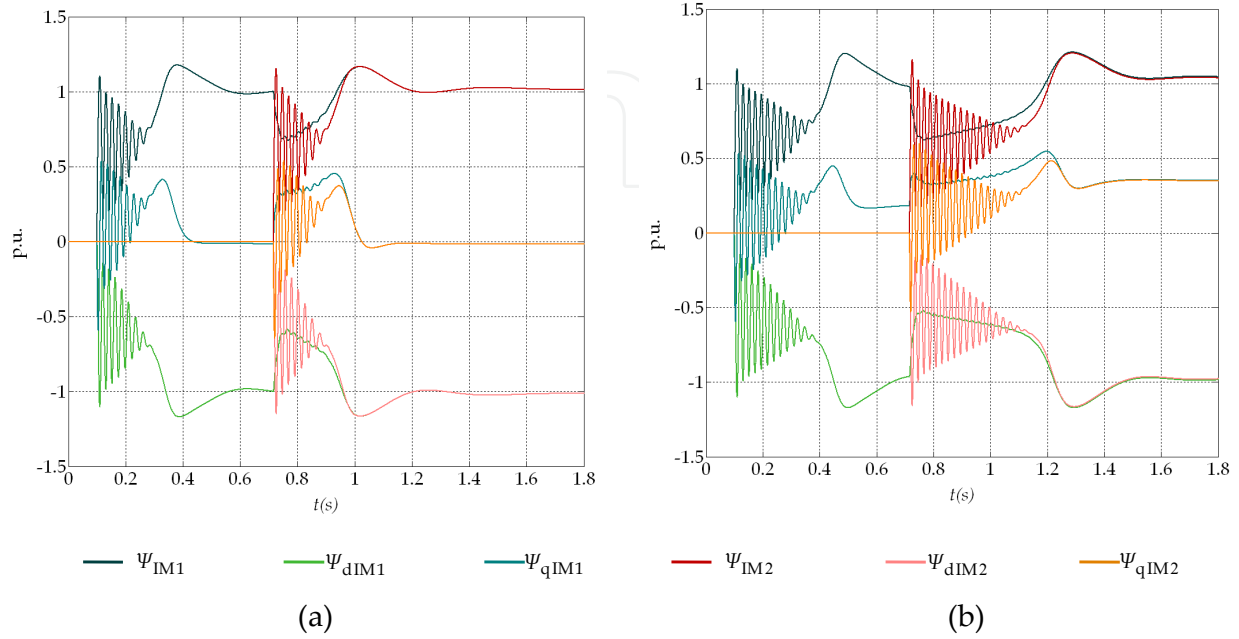

Figure 6. Transients of stator flux linkages of induction motors (Ψ_{IM1}, Ψ_{IM2}) and their components in d (Ψ_{dIM1}, Ψ_{dIM2}) and q (Ψ_{qIM1}, Ψ_{qIM2}) axis during direct-on-line starting of: a) unloaded b) loaded induction motors
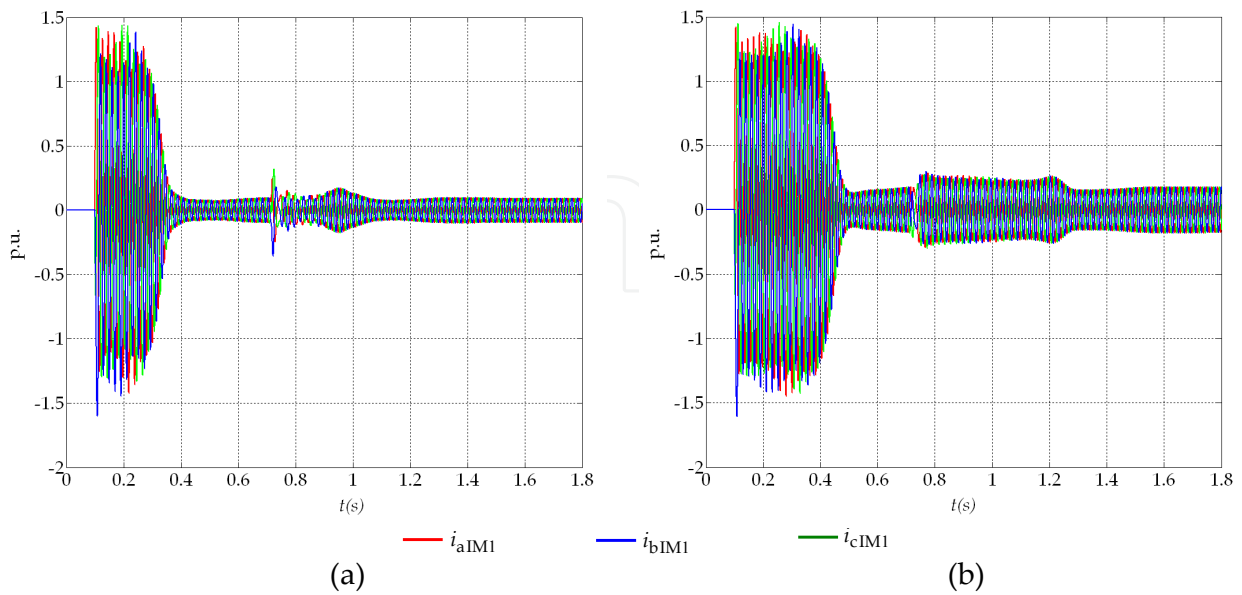
Figure 7. Stator current (i_{abcIM1}) of first induction motor, during direct-on-line starting of: a) unloaded b) loaded induction motors
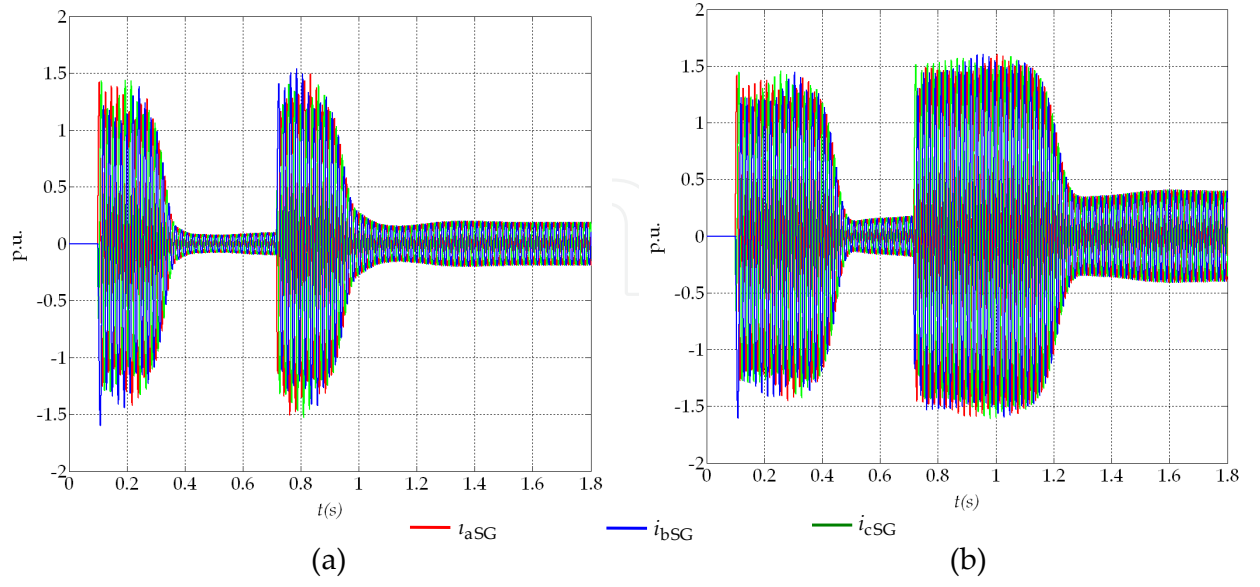
Figure 8. Stator current (i_{abcSG}) of the grid (synchronous generator), during direct-on-line starting of:
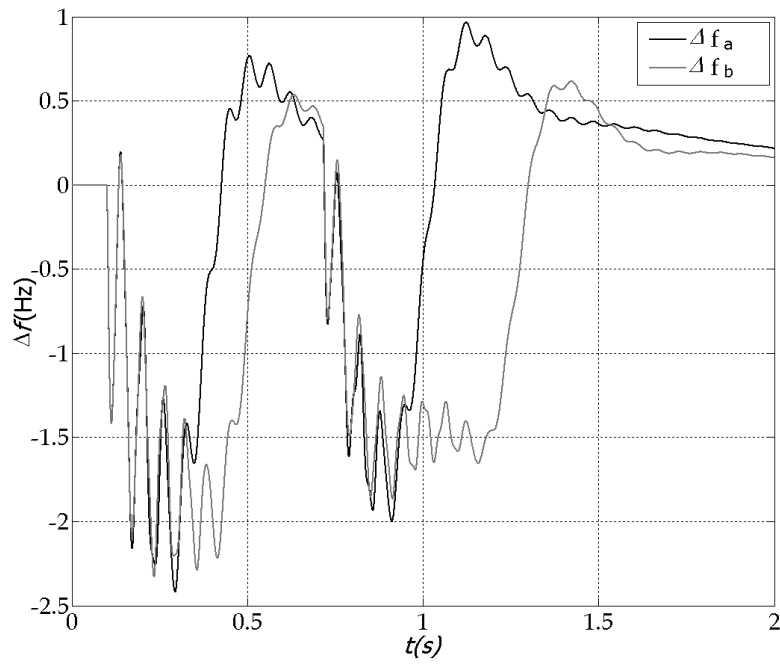a) unloaded b) loaded induction motors

Figure 9. Frequency variations during direct-on-line starting: Δf_a-motors are unloaded, Δf_b -motors are loaded
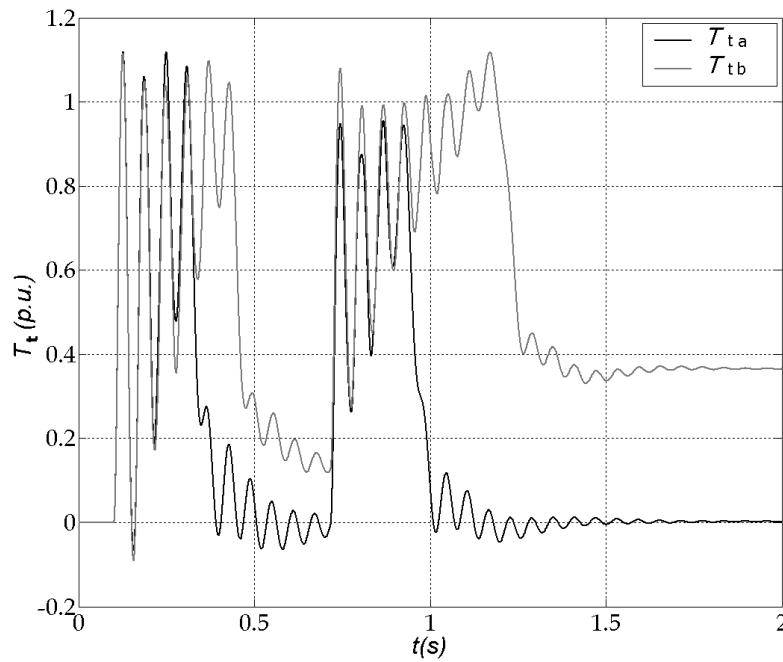
Figure 10. Torsional torque during direct-on-line starting: T_{ta}-motors are unloaded, T_{tb}-motors are loaded

4. Induction motor under sudden change load

The dynamics of sudden change load on the motor shaft is considered. Induction motors are connected directly to the grid, as in previous case, and at chosen moment the first induction motor is starting up, loaded of T_{lIM1} =0.05 p.u. When the first motor has run-up successfully, the second induction motor (IM2) is connected and it starts with T_{lIM2} =0.05 p.u. load on its shaft. Before the second induction motor is connected to the grid the aggregate was led to the steady operation conditions. During start-up of the second induction motor, sudden load change at the first induction motor shaft appeared.

Two cases are considered. In the first case, the impact load of additional 0.1 p.u. on the first induction motor IM1, is applied. While in the second case, the motor is suddenly unloaded, 0.05 p.u. is disconnected from its shaft. Thus, after disconnecting the load the first induction motor run at idle. Transients of air-gap torque and speed transient of induction motors for both cases are presented in Figure 11 and 12.

Direct on line starting of induction motors induces high strain on the power system. This strain arises when the second motor is connected, and additionally is growing up at the instant of impact 0.1 p.u. load on the first motor shaft. When the second induction motor is connected to the grid, it begins to accelerate and the torque of the first induction motor is changed. The electromagnetic torque of the first induction motor becomes negative and motor speed slows down, achieving about 0.95 p.u. Later on, the speed of the first induction motor starts recovery. At the instant of impact additional load on the motor shaft the speed

is decreasing again. The speed of the first induction motor is recovering with strongly damped oscillations at the end of start-up period of the second induction motor (Fig. 11a and Fig. 12a).
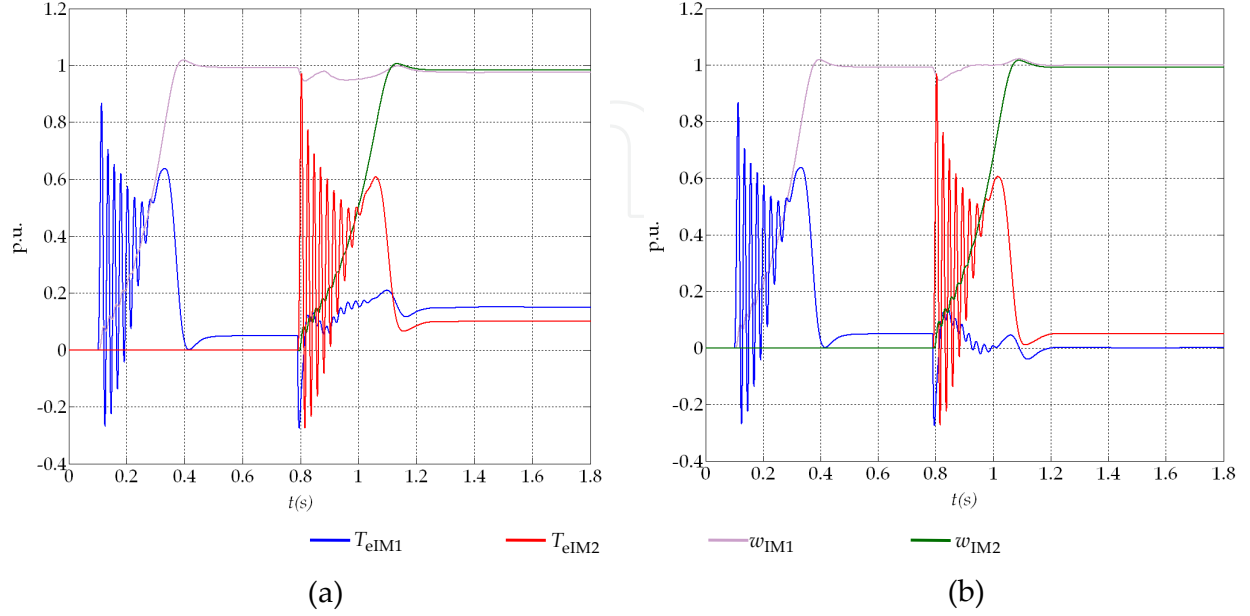

(a)   (b)

Figure 11. Transients of: air-gap torque (T_{eIM1}, T_{eIM2}) and speed transient of induction motors (ω_{IM1}, ω_{IM2}); during sudden change load: a) impact load b) load disconnected
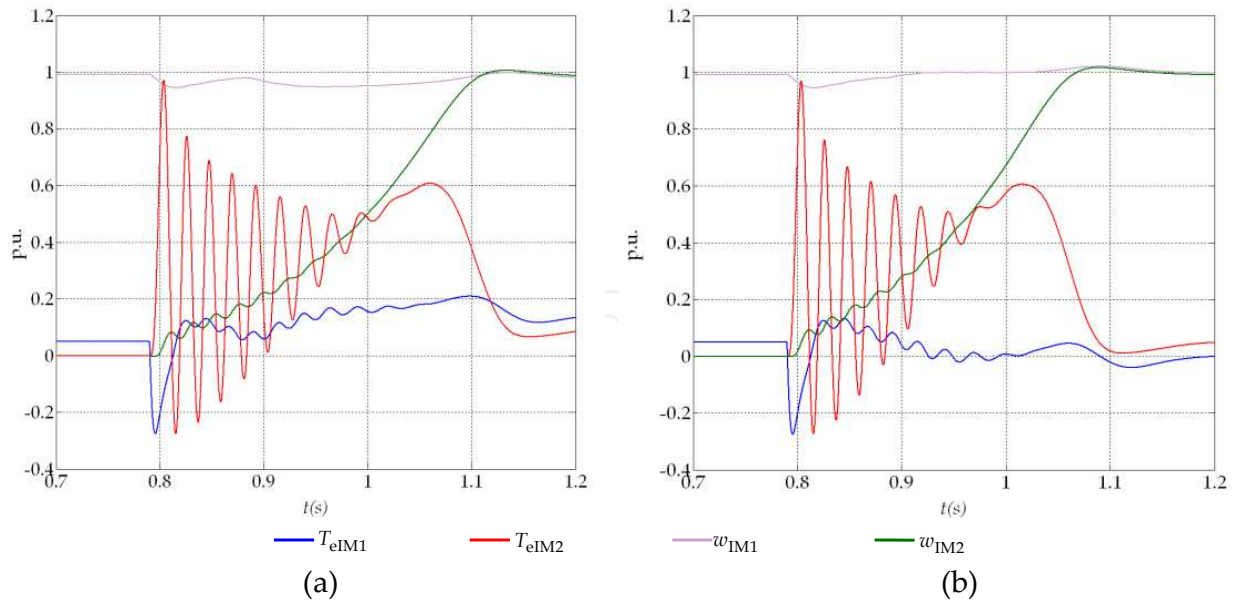

(a)   (b)

Figure 12. Transients of: air-gap torque (T_{eIM1}, T_{eIM2}) and speed transient (ω_{IM1}, ω_{IM2}); during sudden change load: a) impact load b) load disconnected, detail of Fig. 11.

Transients of stator currents of induction motors and their components, for both cases, are presented in Figure 13. The current of the first motor, at the moment of connection IM2,

momentarily increases to 0.31 p.u. and then, with damped oscillation tend to decrease. At the moment of impact additional load the current of the first induction motor is growing up (Fig. 13a). Air-gap torque of the first induction motor, after short term negative value of 0.27 p.u., oscillate about the positive average and tend to decrease.
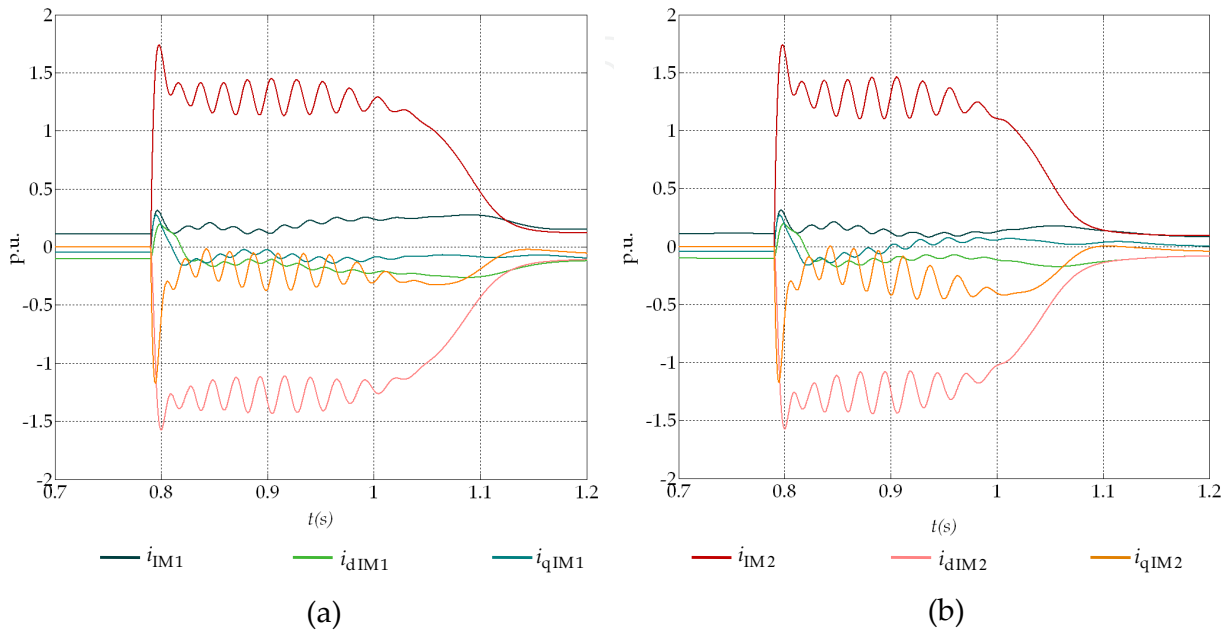

Figure 13. Transients of stator currents of induction motors (i_{IM1}, i_{IM2}) and their components in d (i_{dIM1}, i_{dIM2}) and q (i_{qIM1}, i_{qIM2}) axis during sudden change load: a) impact load b) load disconnected

Thereafter, the air-gap torque is increased, oscillates about the higher positive average then before impact additional load. The electromagnetic torque, as one can see in Fig. 12a, with damped oscillation reaches maximal value of 0.2 p.u. at the end of the start up period of the second induction motor.

The inrush current that is appeared at the beginning of the start-up period of the second induction motor reaches the magnitude of the first oscillation of 1.73 p.u. This current causes the voltage drop at the motor terminals that are connected on the same grid as the second one. The voltage drop results that the motor speed slows down. Because the motor rotor slows down the higher current is appeared on the grid and voltage are reduced even more.

As the additional load is connected the voltage is slowly recovered and start-up period of the second induction motor takes 300 ms.

In the second case, the motor is suddenly unloaded, 0.05 p.u. is disconnected from its shaft at the beginning of the start-up period of the second induction motor. After starting, the second motor begins to accelerate and the torque of the first one is changed, as mentioned before it becomes negative and motor speed slows down. Thereafter, the speed of the first

induction motor continues recovering the whole start-up period of the second induction motor (Fig. 11b). At the moment of sudden unload, the current of the first motor continues decreasing and with damped oscillation reaches steady state (Fig. 13b). Air-gap torque of the first induction motor continues decreasing reaches steady state faster than in the first case, in case of sudden impact load (Fig. 12b).

The inrush current that is appeared at the beginning of the start-up period of the second induction tends to reducing, and after the first induction motor is suddenly unloaded continues decreasing (Fig. 13b). Oscillations in transients of air-gap torque are shorter present and are damped at the end of start up period of the second induction motor, as one can see in figure (Fig. 12b). Corresponding transients of stator flux linkage, in both cases, are presented in Fig. 14. As the grid is unloaded the voltage is recovered, and start-up period of the second induction motor is now shorter, it takes about 260 ms.
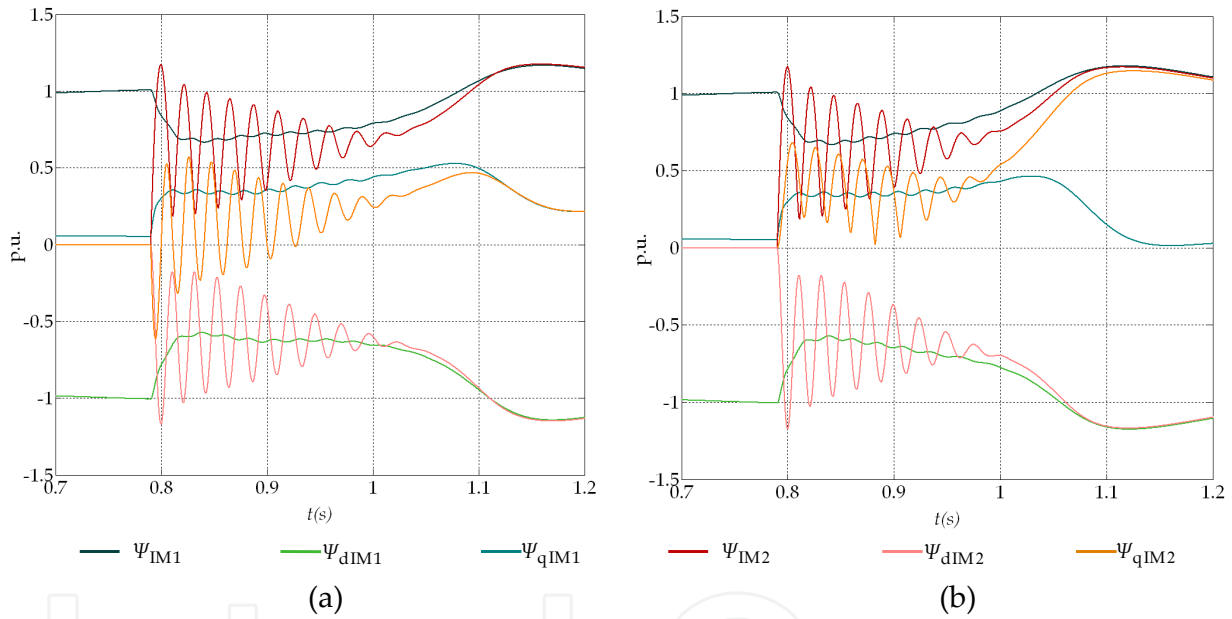

(a)   (b)

Figure 14. Transients of stator flux linkages of induction motors (Ψ_{IM1}, Ψ_{IM2}) and their components in d (Ψ_{dIM1}, Ψ_{dIM2}) and q (Ψ_{qIM1}, Ψ_{qIM2}) axis during sudden change load:
a) impact load b) load disconnected

The transients of the first induction motor current in *abc* coordinate system (i_{abcIM1}), in both cases, are presented in Fig. 15, while the current of synchronous generator (i_{abcSG}) is presented in Fig. 16.

Frequency variation during sudden change load is presented in Figure 17 and, as one can see, that impact load on the motor shaft results in short-term frequency decreasing. When load is switched off, short-term increase of frequency is appeared. Sudden change load affects on speed of aggregate and torque in the coupling, for both cases, is presented in Figure 18.
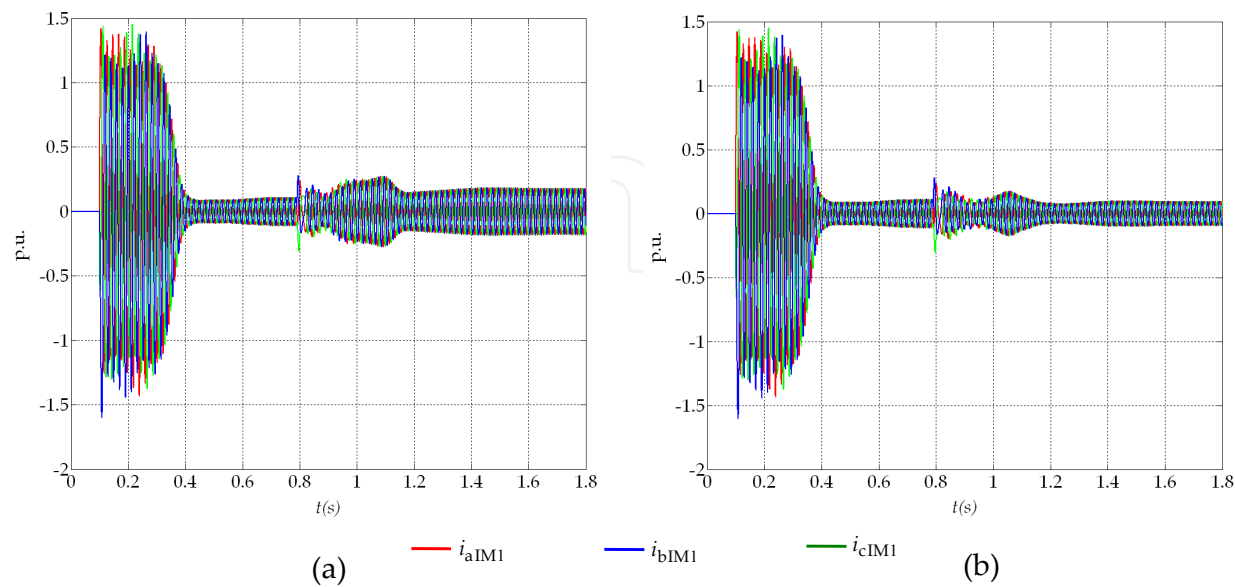
Figure 15. Stator current (i_{abcIM1}) of first induction motor, during sudden change load: a) impact load b) load disconnected
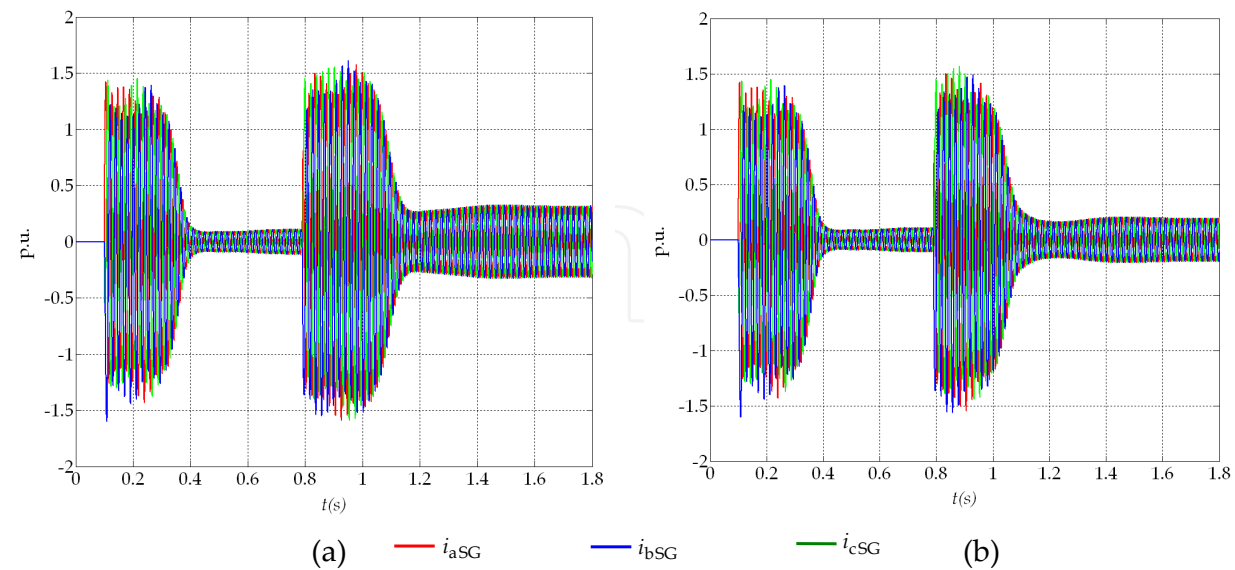

Figure 16. Stator current (i_{abcSG}) of the grid (synchronous generator), during sudden change load: a) impact load b) load disconnected
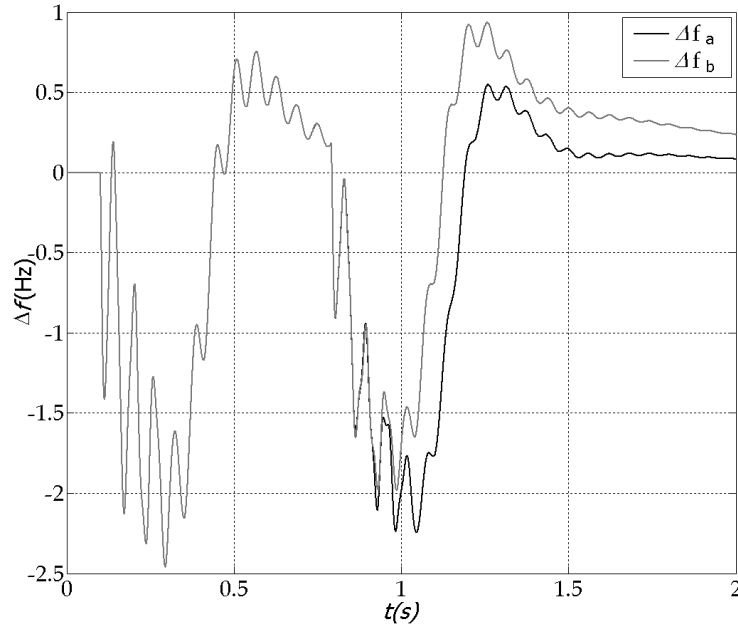
Figure 17. Frequency variations during sudden change load: Δf_a–impact load, Δf_b-load disconnected
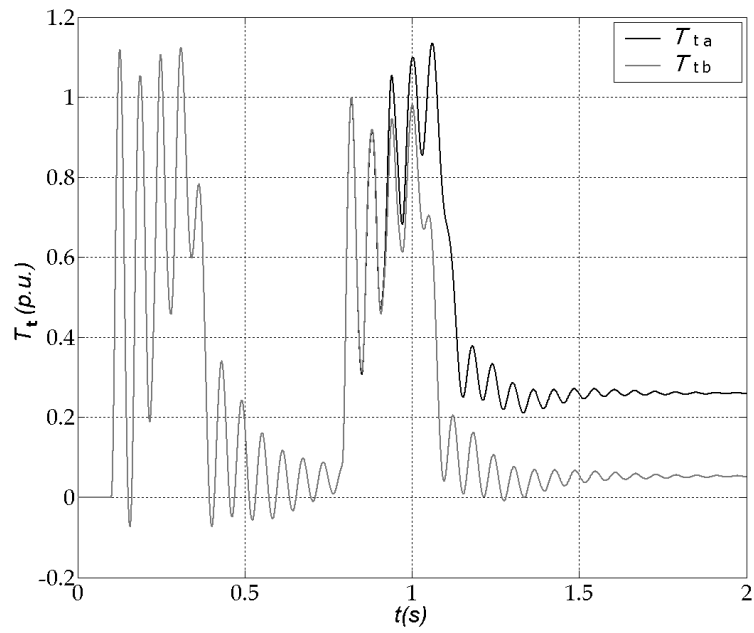

Figure 18. Torsional torque during sudden change load: T_{ta}-impact load, T_{tb}-load disconnected

5. Induction motor under short term voltage interruption

With the aim to get a better insight into the dynamics of induction motor fed directly from the isolated electrical grid the short-term interruptions in the motor power supply are considered.

Direct starting of induction motors on an isolated electrical grid produce disturbance for supply network and local consumers. This disturbance, such as voltage dips and reduction of aggregate speed, will cause decrease of network power quality. The significant voltage dips appear due to faults in power supply, and also, due to certain faults on loads connected to the isolated electrical grid. These voltage dips cause changes in transients of induction motors, as well as in transients of diesel generator unit. Besides the voltage dips, voltage interruption can also appear, which further effects the operation of the induction motor.

Two cases are considered. In the first case, a short term interruption appeared after both motors have run-up successfully. In that moment motors are in steady state condition. In the second case, interruption of power supply on the first induction motor appeared at the beginning of the start up period of the second one.

Motors are started loaded and load on the first induction motor shaft is 0.1 p.u., while the load of 0.05 p.u. is applied on the second induction motor shaft. At the beginning, the first induction motor (IM1) starts and after it has run-up successfully, the second one (IM2) is connected to the grid. At the chosen moment, as motors are in steady state condition, the first induction motor is shortly disconnected from the network, and then, after 100 ms reconnected to the power supply (Fig. 19 and 20).

At the time of voltage interruption, a large negative impulse of the torque of the first induction motor occurs. This reverse torque impulse rapidly decays and the air-gap torque (T_{eIM1}) becomes equal to zero. Changes in the electromagnetic torque of the second induction motor (T_{eIM2}) occurs at the time of disconnection of the first one.

Transients of air-gap torque and speed transient of induction motors; during the short-term interruptions that is appeared on the first induction motor, in case of steady state condition is presented in Figure 19a. However, in Figure 19b, the transients obtain in case of interruption in the first induction motor power supply that appeared at the beginning of the start up period of the second induction motor is presented. Transients of stator currents of induction motors and their components in d and q axis during the short-term interruptions, for both cases are presented in figure 20.

As one can see in Fig. 20a, at the time of voltage interruption, current of the first induction motor momentarily reaches approximately 2 p.u., while current of the second one reaches approximately 0.6 p.u. Thus, by restoring the supply, at the beginning of the transients the current of the first induction motor momentarily reaches 2 p.u., at the same time as the current of the second induction motor reaches maximal value of 0.35 p.u. A negative impulse of the torques T_{eIM1} and T_{eIM2} instantaneously appears. Thus, the speed of the first induction motor at the beginning of the transients additionally is shortly decreased, and afterwards continues recovering.

At the instant of the supply recovery air-gap torque of second induction motor suddenly reaches negative value and, as one can see in Fig. 21a, the speed of second induction motor is decreased and than rapidly recovers.
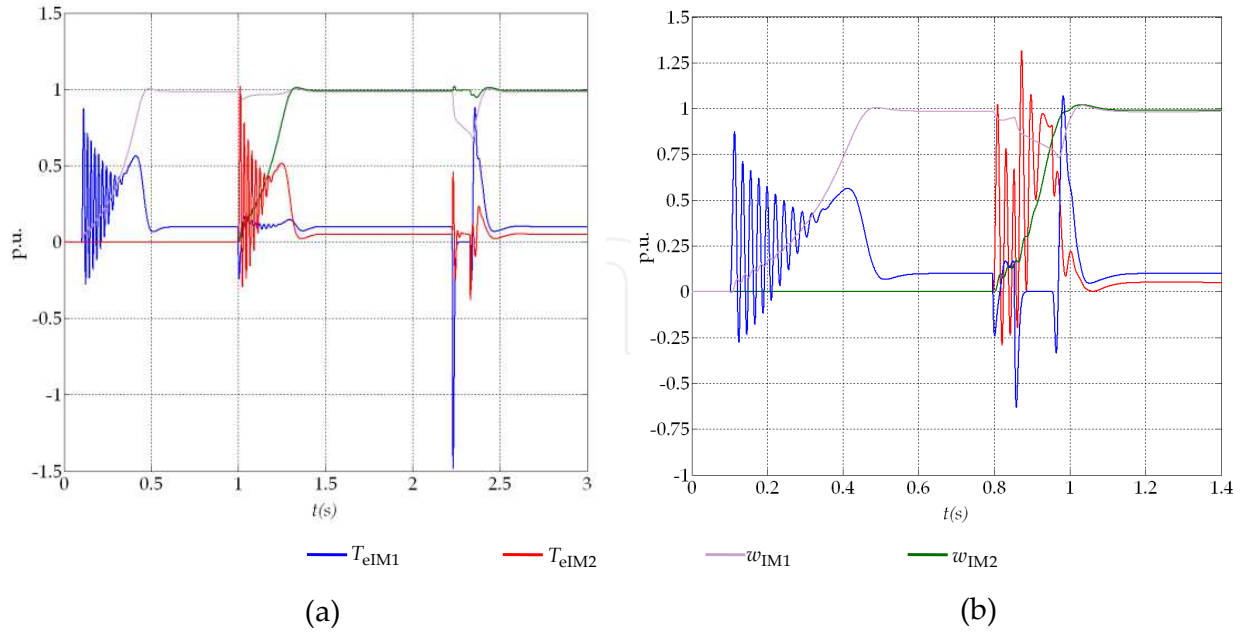
Figure 19. Transients of: air-gap torque (T_{eIM1}, T_{eIM2}) and speed transient of induction motors (ω_{IM1}, ω_{IM2}) during the short-term interruptions that is appeared on the first induction
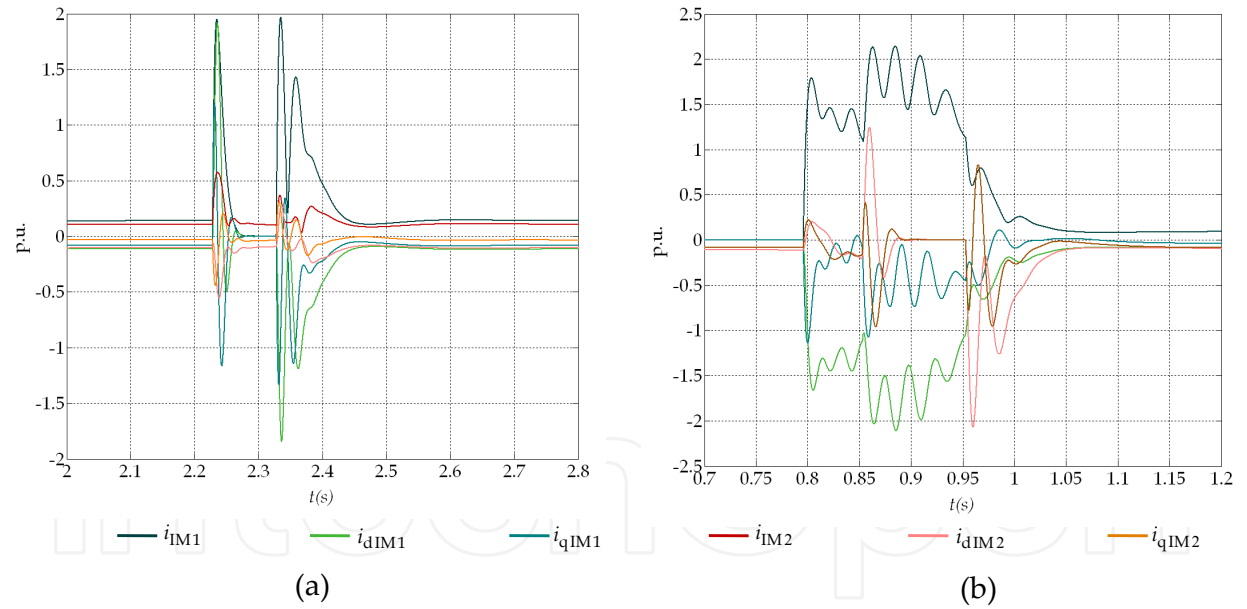

Figure 20. Transients of stator currents of induction motors (i_{IM1}, i_{IM2}) and their components in d (i_{dIM1}, i_{dIM2}) and q (i_{qIM1}, i_{qIM2}) axis during the short-term interruptions: a) motors are in steady state condition b) at the beginning of the start up period of the second one

In the second case, interruption in the first induction motor power supply appeared at the beginning of the start up period of the second induction motor.

At the time of connecting the second induction motor, the current is momentarily increased to 1.7 p.u. and has a decreasing tendency. By the time of short term power interruption on

the first induction motor, the current of the second one suddenly increases to 2.2 p.u. Further, the current oscillates around a higher average value than before and the damped oscillations are rapidly decreasing (Fig. 20b).

The transient of air-gap torque of induction motors are presented in Fig. 21. However, the air-gap torque of the first induction motor, at the time of voltage interruption occurred, momentarily reaches negative impulse of approximately 0.6 p.u. (Fig. 21b). The speed of the first induction motor (IM1) decreases at the beginning of the start up period of the second induction motor and tend to increase when fault occurs. As voltage interruption occurred the speed continuous reducing. In the speed transient of the second induction motor (IM2) one can see that is short term decreased appeared at the beginning of interruption and after that the motor continuous accelerates.
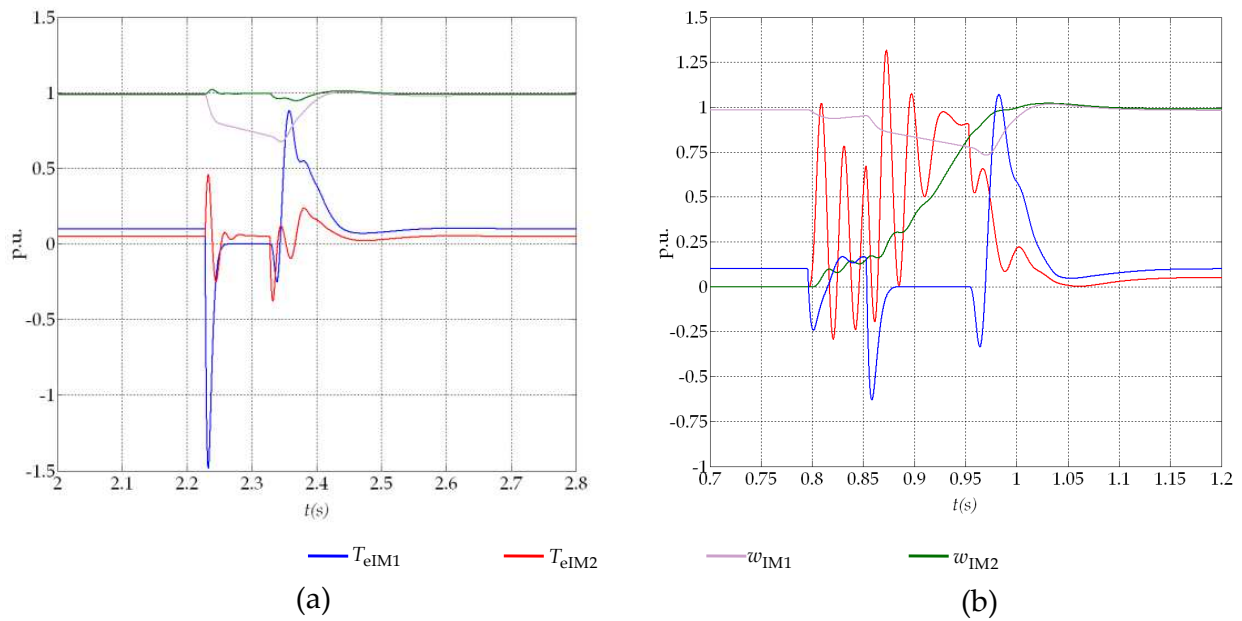

Figure 21. Transient of electromagnetic torque (T_{eIM1}, T_{eIM2}) and speed transient of induction motors (ω_{IM1}, ω_{IM2}); during the short-term interruptions: a) motors are in steady state condition b) at the beginning of the start up period of the second one detail of Fig. 20.

Terminal voltage (u_{abcIM1}) of the first induction motor, during the short-term interruptions, for the both cases is presented in Figure 22, while corresponding stator currents (i_{abcIM1}) of first induction motor are shown in Figure 23.

The voltage dips as well as voltage interruption, which further effects the operation of the induction motor, causes changes in transients of diesel generator unit. A short-term power interruption will result, as shown, in significant changes of electrical and mechanical variables and will also cause torsional strain in the shaft line. The mechanical coupling of a diesel engine and a synchronous generator is considered to be a rotating system with two concentrated masses that are connected by flexible coupling. The flexible coupling allows these masses to rotate at a different speed in transients. Thus, in Fig. 24 the speed transients of diesel engine and synchronous generator are presented, while torque at coupling zone is presented in Figure 26.
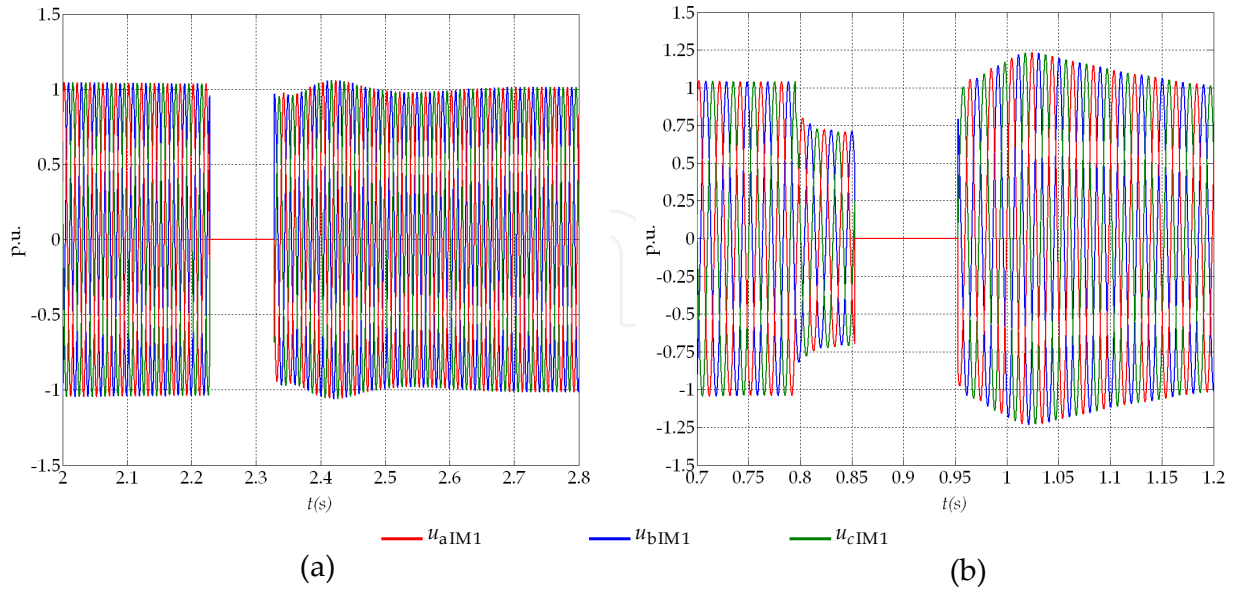
Figure 22. Voltage (u_{abcIM1}), during the short-term interruptions: a) motors are in steady state condition b) at the beginning of the start up period of the second one
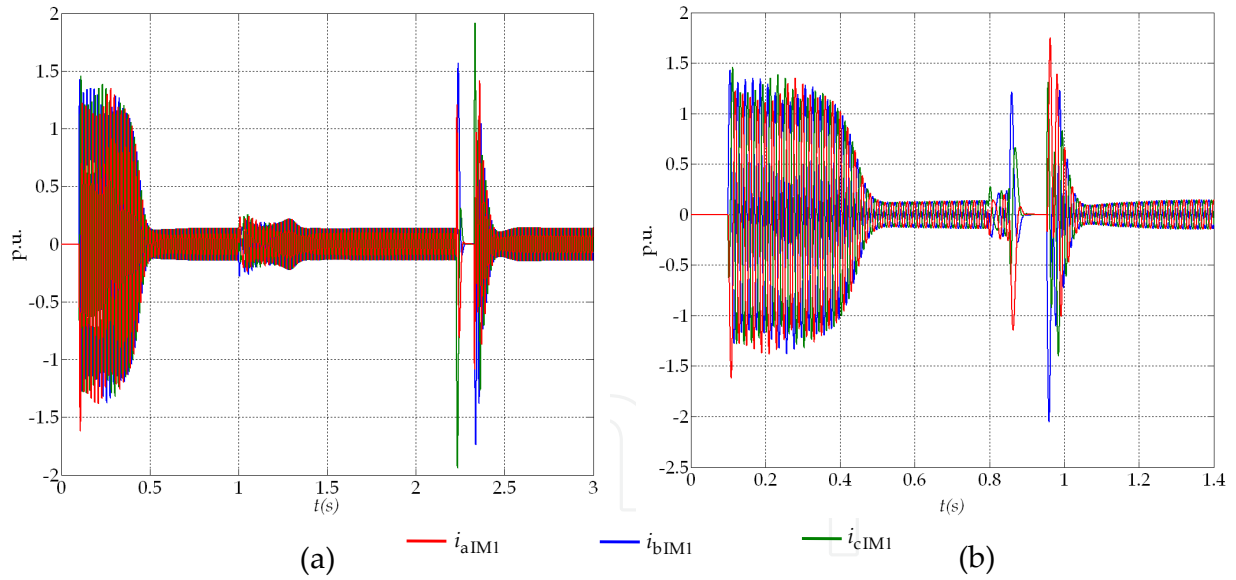

Figure 23. Stator current (i_{abcIM1}) of first induction motor, during the short-term interruptions: a) motors are in steady state condition b) at the beginning of the start up period of the second one

Sudden impact load on the isolated electrical grid induces a large strain on the diesel generator unit shaft. After the first induction motor is started, the diesel engine accepts the load and later reaches the steady speed. As a result of the starting of the loaded IM2, the speed of the diesel engine decreased and reached a minimum value of 0.97 p.u., while the speed of the synchronous generator reached a value of about 0.96 p.u. (Fig. 24a).
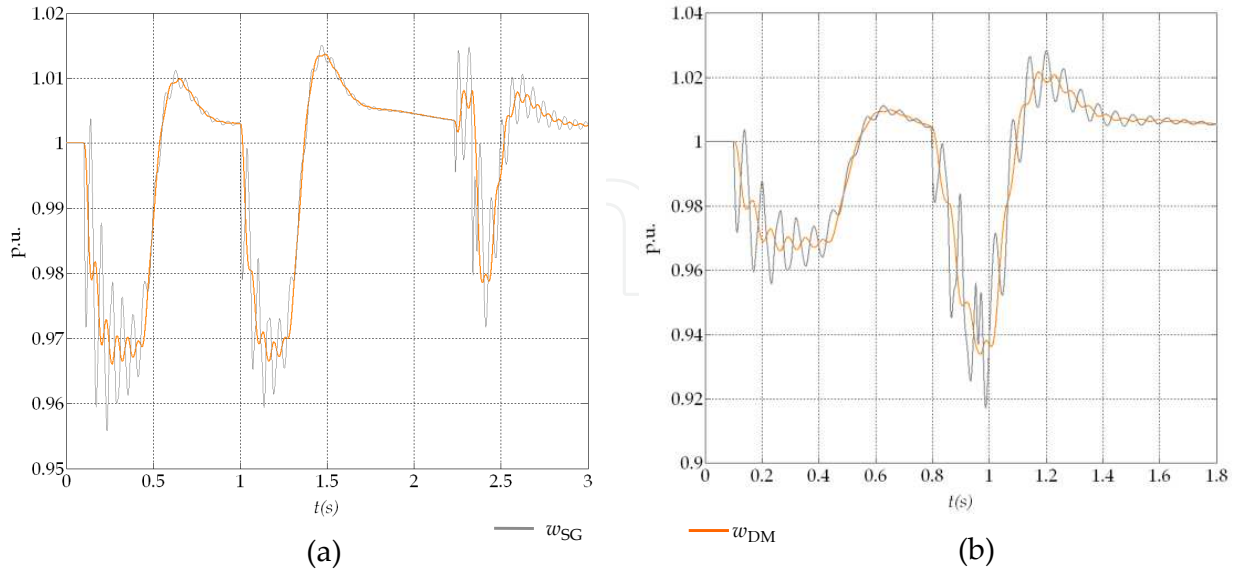
Figure 24. Speed transient of synchronous generator (ω_{SG}) and diesel engine (ω_{DM}) during the short-term interruptions: a) motors are in steady state condition b) at the beginning of the start up period of the second one
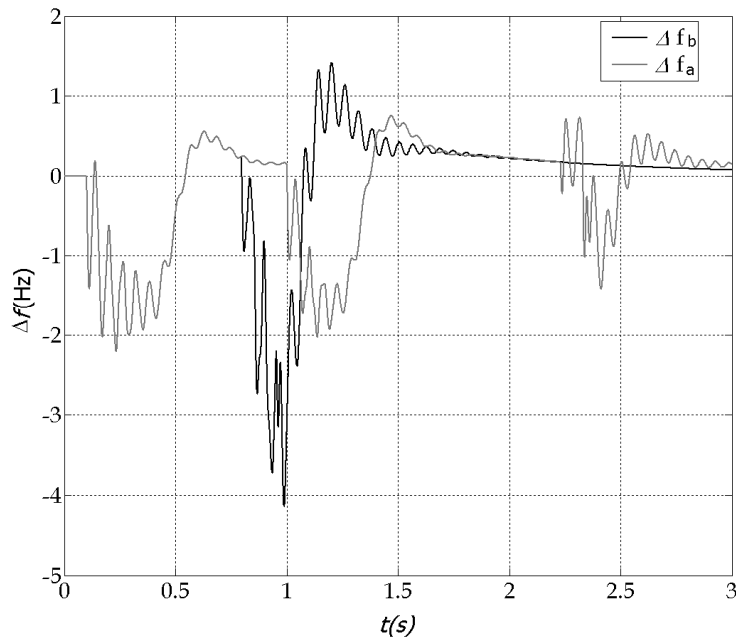

Figure 25. Frequency variations during short-term interruptions: Δf_a- motors are in steady state condition, Δf_b- at the beginning of the start up period of the second one
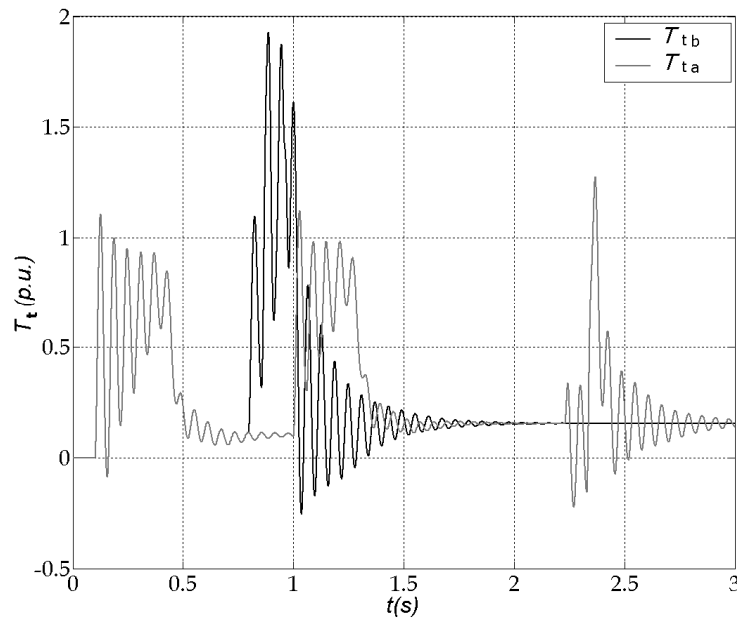
Figure 26. Transient of torsional torque during short-term interruptions:
T_{ta}-motors are in steady state condition, T_{tb}- at the beginning of the start up period of the second one

Occurrence of short-term power loss, at the time that motors are in steady state condition, speed of both machines increased. After, reconnected to the power supply the speed of synchronous generator as well as induction motor is reduced. Damped oscillations are presented during transients. In the second case, when the short-term interruption occurs at the beginning of the start up period of the second induction motor, speed of both machines continue decrease. In this case, the speed of synchronous generator is reduced to less of 0.92 p.u., while the speed of the diesel engine is reduced to less of 0.94 p.u. The oscillations appear with greater magnitude then in previous case. Speed deviation affects on frequency of grid and frequency variations during short-term interruptions, for both cases are presented in Figure 25. Significant disturbances appear in transients of torsional torque especially in case when short-term interruptions is appear at the beginning of the start up period of the second induction motor, as one can see in Figure 26.

6. Discussion

The dynamics of induction motors fed directly from the isolated electrical grid is considered in the cases of: direct-on-line starting of induction motors, sudden change load on the motor shaft and during short-term voltage interruptions. Direct on line starting of induction motors on the isolated power system is the most difficult transition regime for units due to electricity loads and also due to torsional loads on the shaft line. 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. During starting induction motors draw high starting current, known as locked rotor current,

which are several times the normal full load current of the motor. This current causes a significant voltage dip on the isolated electrical grid, the terminal voltage is momentary decreased and after few damped oscillations reached minimal value. During this short period the voltage regulator does not affect jet. The voltage drop increases in case of starting loaded induction motor, the current momentarily reaches higher value of first magnitude and oscillates about higher average value than in previous case.

Disturbances in the system are present when the second induction motor is connected to the grid and additionally is growing up at the instant of impact additional load on the previous induction motor shaft. As load on the motor shaft grows up, the current of the motor is higher; oscillations are more damped and longer present in comparison with lightly load or no-loaded induction motor.

This current causes the voltage drop at the motor terminals that are connected on the same grid. The mutually effect between source and loads exists. The voltage drop results that the motor speed slows down. Because the motor rotor slows down the higher current is appeared on the grid and voltage are reduced even more.

At the instant of starting of induction motors the locked rotor torque appeared and as the rotor starts to rotate the air-gap torque oscillates about positive average value. Oscillations in transient of electromagnetic torque are damped at the end of start up period and finally the steady state condition is attained without oscillations. The oscillations are longer presented in case of bigger load torque on the motor shaft. Sudden change load on the motor shaft causes changes in air-gap torque. Damped oscillations are longer present in a case of impact additional load than during load disconnected. Both cases influence on the electrical grid and changes in transients of both induction motors as well as in synchronous generator are present.

The start-up period of the induction motor is longer when the bigger load torque on the motor shaft is applied. Also, decreasing the terminal voltage causes longer duration of speed transient in dynamics.

Sudden change load on a motor shaft, which occurs during operation period, results in speed change of the other motors that fed from the same grid.

Direct starting of induction motors on isolated electrical grid, as well as sudden change load, caused voltage dips and also reduces speed of aggregate. The significant voltage dips appear due to faults in power supply, as well as certain faults on loads connected to isolated electrical network. Besides the voltage dips, voltage interruption can also appear. This causes significant disturbances on the grid and affects the operation of other induction motor. If interruption of the supply lasts longer than one voltage period, many AC contactors will switch off the motor. However, in some cases, faulty contactor may produce multiple on and off switching. These interruptions affect the dynamics of both electrical and mechanical variables, which will also cause torsional stresses in the shaft line. The consequences of voltage interruption on the induction motor behavior are current and air-gap torque peaks that appear at instant of fault and recovery voltage.

Sudden changes of active power have impact on both voltage and frequency but a start-up of electric motor influences disproportionately the voltage value due to relatively low power factor during the process.

7. Conclusion

The dynamics of induction motors fed directly from the isolated electrical grid is analyzed. In isolated electrical grid, such as for example ship's electrical grid, the main source is a diesel generator and induction motors are the most common loads. Induction machine plays a very important role in that application and a significant number of induction motors are used at critical points of on board processes. The connection of large induction motors (large relative to the generator capacity) to that grid is difficult transient regime for units due to electrical loads and also due to torsional loads on the shaft line. Direct on line starting of induction motors induces high strain on the power system and this strain arises when the next induction motor is connected to the grid. Sudden impact load on the induction motors shaft is an additional strain on the network, especially when impact load on a motor shaft occurs during start up of another one. This in turn affects the quality of electric power system and thus, the dynamic behavior of induction motors. The significant voltage dips appear due to faults in power supply, and also, due to certain faults on loads connected to the isolated electrical grid. These voltage dips cause changes in transients of induction motors, as well as in transients of diesel generator unit. Besides the voltage dips, voltage interruption can also appear, which further effects the operation of the induction motor. 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 analyze and document the effect of the additional loads on its normal and transient performance. An induction motor starting study may be of use in analyzing the performance of small power systems. Such systems are usually served by limited capacity sources that are subject to severe voltage drop problems on motor starting, especially when large motors are involved. In some cases, specific loads must be accelerated in specially controlled conditions, keeping torque values in defined limits. The results obtained by this analysis can be used as a guideline in choosing as well as setting parameters of the protection devices.

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