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Study of the behaviour of a doubly-fed induction machine supplied with scalar open-loop control

***Abstract**. Doubly-fed induction machine is usually used in variable-speed electric drives, where the rotor speed is in the vicinity of the synchronous speed. Finite-element-method model has been built and several studies, i. e. start up, sudden load change and fan drive, have been performed in order to verify the machine behaviour in supersynchronous motor operation. The simplest form of control (open-loop U/f control) has been used for rotor voltage supply, while the stator was connected directly to the public network.*

***Streszczenie.** Maszyna indukcyjna dwustronnie zasilana jest zwykle używana w napędach elektrycznych o zmiennej prędkości, gdzie prędkość wirnika jest zbliżona do prędkości synchronicznej. Opracowano model w oparciu o metodę elementów skończonych. Przeprowadzono doświadczenia, w których zmieniano parametry rozruchu, obciążenie i wentylator w celu sprawdzenia zachowania maszyny w trybie pracy silnika supersynchronicznego. Najprostsza forma sterowania (sterowanie U/f w otwartej pętli) została wykorzystana do zasilania napięciowego wirnika, podczas gdy stojan został podłączony bezpośrednio do sieci publicznej. (**Badanie zachowania maszyny indukcyjnej dwustronnie zasilanej ze sterowaniem w pętli otwartej**).*

Keywords: doubly-fed induction machine, supersynchronous motor operation, open-loop control
Słowa kluczowe: maszyna indukcyjna dwustronnie zasilana, supersynchroniczna praca silnika, sterowanie w pętli otwartej
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Introduction

Doubly-fed induction machine (DFIM) is usually used in large-power variable-speed drives with limited range of speed in the vicinity of the synchronous speed using bidirectional power converter [1-5], e. g. wind turbines, large pumps etc. Stator is connected directly to the public network (400 V and 50 Hz in Europe), whereas rotor is connected to the same network via power converter with adjustable voltage and frequency (Fig. 1).

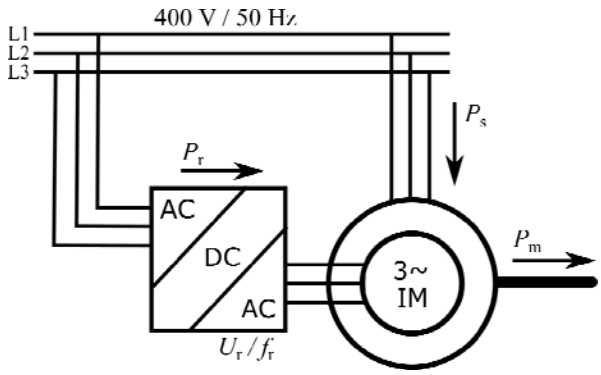

Fig.1. Power flow in the drive system with DFIM and power converter

If power converter (rotor voltage source) allows only unidirectional power flow (Fig. 1), i. e. from the network to the machine (diode rectifier at the input side instead of the transistor bridge), then the operational area is limited to the supersynchronous speeds [6-7], assuming that the machine operates as a motor (Fig. 2). The power rating of the rotor voltage source is a fraction of the total power and it increases with increasing speed range [8-10].

In the steady-state motor operation, the rotor rotates in the supersynchronous area with the mechanical speed, which is defined as the sum of the rotational frequency of the stator and rotor rotating magnetic field, divided by the number of pole pairs:

$$\Omega = \frac{\omega_1 + \omega_2}{p} \quad (1)$$

where: Ω – mechanical speed in [1/s], ω_1/ω_2 – angular frequency of the stator/rotor voltage in [1/s], p – number of pole pairs.

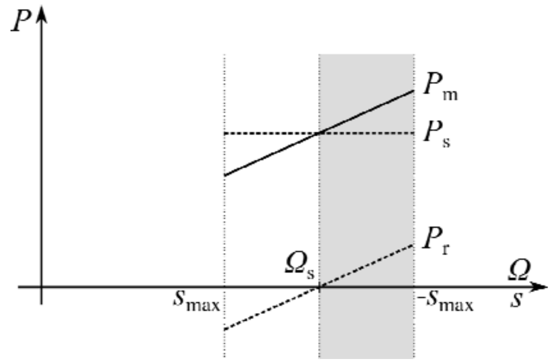

Fig.2. Supersynchronous motor operation area (grey)

Simulated drive system

The two-dimensional finite-element-method (FEM) model (Fig. 3) with analytically calculated resistances and end-winding leakage inductances was built in order to obtain as accurate results as possible. The machine data are given in Table 1. The scalar open-loop control with variable voltage-to-frequency ratio (*U*/*f* control) has been used for the rotor voltage source in the simulations. Namely, the *U*/*f* control it is one of the simplest, easy-to-design and low-cost motor control methods [11-12], thus the drive system was simplified as much as possible.

Table 1. Machine data

Stator outer diameter	150.0 mm
Stator inner diameter	103.0 mm
Rotor outer diameter	102.0 mm
Shaft diameter	36.0 mm
Core axial length	120.0 mm
Number of pole pairs	3
Number of stator slots	36
Number of rotor slots	27
Stator-tooth width	4.4 mm
Rotor-tooth width	5.3 mm
Stator-yoke thickness	10.0 mm
Rotor-yoke thickness	11.0 mm
Stator nominal voltage	400 V
Rotor nominal voltage	100 V
Nominal power	1.5 kW

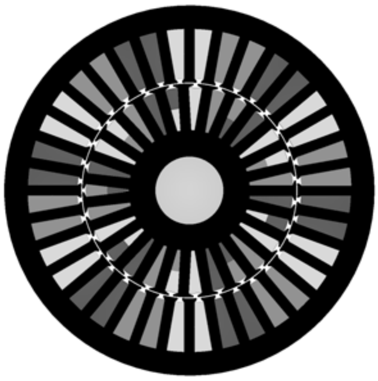

Fig. 3. Cross section of the FEM model of the DFIM

Due to the open-loop control, the speed or position sensor is not needed, which increases the mechanical robustness of the drive system. The DFIM is able to self-synchronize to the supersynchronous speed, defined by equation (1). The synchronisation can be lost in case of large sudden load torque changes. Loss of synchronisation can be detected indirectly without measuring the speed but one of the electrical quantities instead, e. g. the active power, dc-link current or motor phase currents (either stator or rotor) [13].

Simulation of the start-up

When the stator and rotor rotating magnetic field of the DFIM are not in synchronism, the machine produces average electromagnetic torque, different from zero, which tends to synchronise both rotating magnetic fields. This means that the machine is able to reach synchronism from standstill, even without any complex control of the rotor source (simple three-phase voltage supply in both sources) and without any kind of sensor. The machine is able to start at the direct connection to the voltage sources (self-starting). However, sufficient magnetisation (for this case it will explained in the following text), i. e. sufficient *U/f* ratio, from rotor side is needed in order to achieve synchronisation, especially when there is load torque present already from the start. In case of insufficient rotor magnetisation, the machine speed and torque may start to oscillate and the synchronisation may not be achieved.

Fig. 4-6 show results of the simulations with successful as well as unsuccessful start-ups. Stator is connected directly to the three phase network and rotor is supplied with sinusoidal voltage source with variable voltage and frequency. Sinusoidal rotor voltages have been taken into account because the general behaviour of the drive has been studied, although in reality the rotor would be supplied with PWM voltage, which introduces additional higher harmonic components of the voltage and current. The rotor voltage amplitude and frequency that have been applied in each case are gathered in Table 2.

Table 2. Rotor voltage at different start-up simulations

Simulation	U_r [V]	f_r [Hz]
No-load start up (AC)	15	10
Start-up under load (AC)	30	10
Start-up under load (DC/AC)	10/30	0/10

In Fig. 4, successful start-up with no load is shown. After approximately 0.1 s, the machine reaches synchronism at 1200 min^{-1} (50 Hz on the stator side, 10 Hz on the rotor side, 3 pole pairs). The electromagnetic torque that the machine produces in the steady state is approximately 0 Nm.

If the machine is started under constant torque of 10 Nm, which is approximately 70 % of the nominal torque, the synchronism is not achieved (Fig. 5), although the amplitude of the rotor voltage is doubled. The electromagnetic torque and rotor speed oscillate. A procedure for a successful start-up under load torque is suggested here. First, the d. c. voltage instead of the a. c. voltage is applied to the rotor winding. The voltage has to be large enough to sufficiently magnetise the machine (10 V d. c. in this case). The DFIM now behaves as classical rotor-excited synchronous machine with additional damper cage on the rotor (current can flow through flywheel diodes in rotor circuit PWM voltage source), which allows synchronisation. The machine reaches stable steady-state operation at synchronous speed (1000 min^{-1}) after approximately 0.1 s (Fig. 6). After that, the a. c. voltage with the same amplitude and frequency as in the previous case (30 V, 10 Hz) is applied to the rotor winding at 0.2 s. The machine accelerates to 1200 min^{-1}, while the electromagnetic torque and speed are stable and do not oscillate.

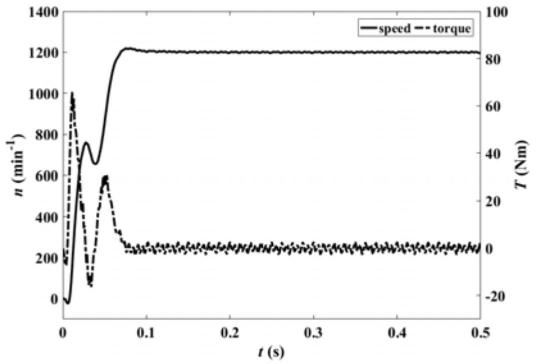

Fig. 4. No-load start up and synchronisation

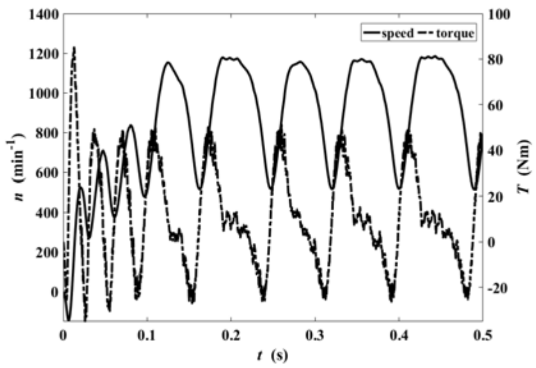

Fig. 5. Start up under load with unsuccessful synchronisation

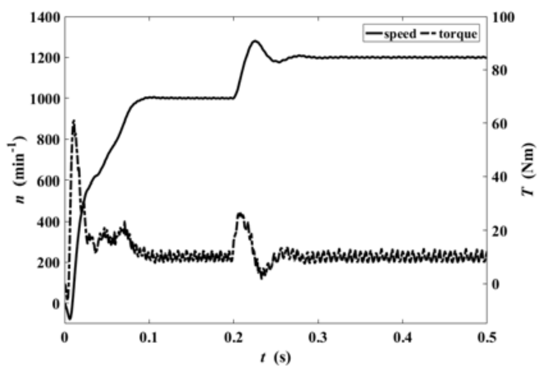

Fig. 6. Start up under load with successful synchronisation

In these three case studies, it has been shown that machine is able to start directly from standstill, if there is no load torque. In case of too large load torque, the start-up consists of two parts – from standstill to synchronism and from synchronism to supersynchronism.

Simulation of the sudden load change

The DFIM response to the sudden change of the load torque shows certain degree of robustness. In all simulations of the sudden load change, a no-load start-up was assumed. In case of the moderate sudden load change of 5 Nm, which is approximately 35 % of the nominal torque, the machine continues to operate in the steady state, after transient phenomenon is finished (Fig. 7).

However, if the sudden load change is large, e. g. 30 Nm or more than 200 % of the nominal torque, the machine loses synchronism and the electromagnetic torque and rotor speed start to oscillate (Fig. 8).

In order to prevent the loss of synchronisation, the rotor voltage amplitude must be increased, when the load torque changes. This is possible only, if the sudden load change is expected. With increased rotor voltage amplitude from 30 V to 50 V and unchanged frequency, the magnetisation level from the rotor side is increased. The machine is able to produce sufficient electromagnetic torque, which maintains supersynchronous steady-state operation (Fig. 9).

Table 3. Rotor voltage at different sudden load change simulations

Simulation	U_r [V]	f_r [Hz]
Sudden unexp. load 5 Nm (AC)	30	10
Sudden unexp. load 30 Nm (AC)	30	10
Sudden exp. load 30 Nm (AC/AC)	30/50	10

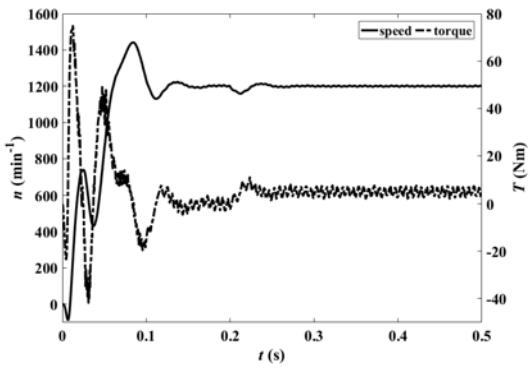

Fig. 7. No-load start up and sudden unexpected load step of 5 Nm

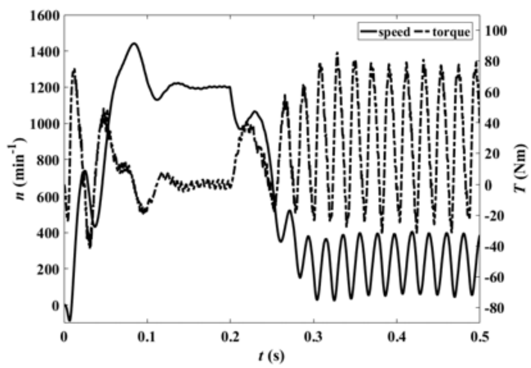

Fig. 8. No-load start up and sudden unexpected load step of 30 Nm

However, if the sudden large load change is not expected and the machine falls out of synchronism, it is still possible to retrieve synchronisation. First, the d. c. voltage is applied to the rotor winding, until synchronous speed is achieved. Then, the a. c. voltage is applied in order to reach desired supersynchronous speed. The procedure for synchronisation retrieving is the same to the previously simulated start-up under load (third case in start-up simulations). The rotor voltage amplitudes and frequencies for the sudden load change simulations are gathered in Table 3.

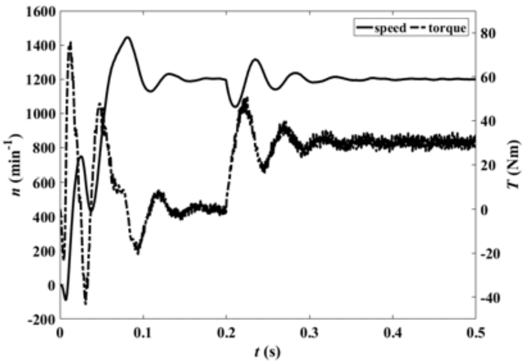

Fig. 9. No-load start up and sudden expected load step of 30 Nm

Simulation of the fan drive

A simulation of a DFIM drive with passive load (fan) was performed. The rotor voltage amplitude and frequency were changed during the simulation and the machine performance was observed.

Since the load has a fan drive characteristic, the load torque increases with square of the rotor speed. Its value is defined with equation (2). The power, needed to drive the fan at 1200 min^{-1}, is then 1.5 kW, which is also nominal power of the machine.

(2) $$T_L = 12\left(\frac{n}{1200}\right)^2$$

where: T_L – load torque in [Nm], n – rotor speed in [min^{-1}].

The start-up is performed with d. c. rotor voltage of 10 V, until synchronous speed is achieved (Fig. 10). Then at 0.2 s, the rotor voltage amplitude and frequency are increased to 35 V and 15 Hz, respectively. The machine operates at 1300 min^{-1} for a certain amount of time – until 0.5 s in this simulation, but this time can be optionally extended. At 0.5 s, the frequency of the rotor voltage is decreased to 10 Hz, while the amplitude remains unchanged. The rotor speed decreases to 1200 min^{-1}. The rotor voltage amplitude is then decreased twice at 1.0 s and 1.2 s with unchanged frequency, which means that the *U*/*f* ratio decreases to 3.0 V/Hz and 2.5 V/Hz, respectively (Fig. 13). This is done in order to reduce the current, flowing through the rotor, and consequently the losses in the rotor winding. Since the mechanical speed is not changed (both the torque and speed are constant) and the stator active power increases only slightly, the efficiency of the machine is increased.

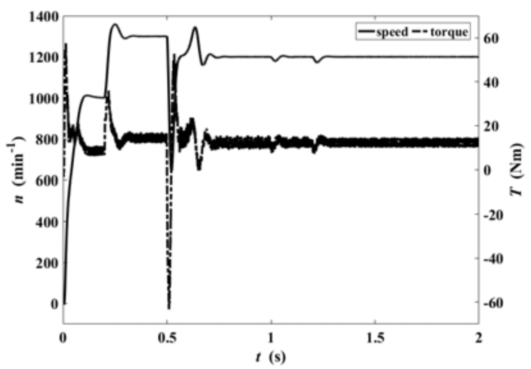

Fig. 10. Speed and torque of a DFIM driving a fan

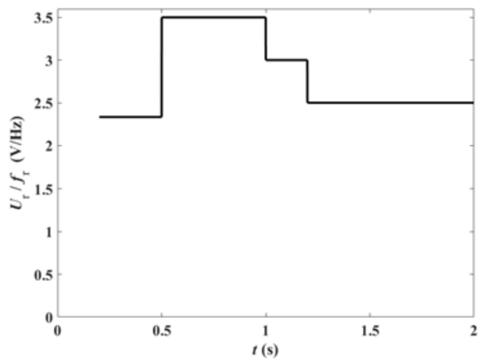

Fig. 11. U/f ratio of the rotor voltage

Another interesting phenomenon can be observed in Fig. 10. At 0.5 s, when the amplitude and frequency of the rotor voltage suddenly change, machine produces a large negative torque (approximately -60 Nm or more than 5 times the nominal torque) for a short period of time, which may cause mechanical damages to the machine or drive.

The reason for such large torque change is sudden rotor voltage change at 0.5 s, which is shown in Fig. 12. The voltage is instantly changed to the opposite value, which causes large currents in the rotor and stator windings and is manifested as large braking torque. However, if the rotor voltage frequency transition is smooth (Fig. 13), no large torque change occurs, as it can be seen in Fig. 14.

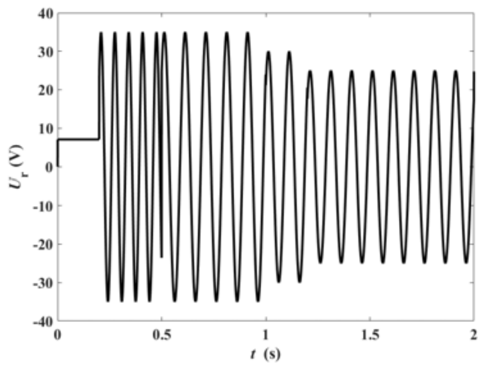

Fig. 12. Rotor voltage against time – frequency change at 0.5 s

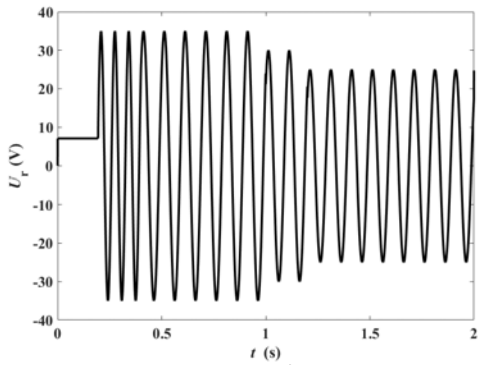

Fig. 13. Rotor voltage against time – frequency change at 0.4 s

In Fig. 15 and 16, the stator and rotor active power are presented, respectively. It can be seen that with the reducing of the *U*/*f* ratio from 3.5 V/Hz to 2.5 V/Hz with a step of 0.5 V/Hz (the part of the graph from 0.5 s to 2.0 s), the average stator active power increases from 1312 W to 1389 W, while on the other hand the average rotor active power decreases from 1828 W to 630 W. The mechanical power is constant during whole time (1508 W), since the rotor speed and torque do not change. In the simulation, the machine efficiency is increased from 48.0 % to 74.7 % just by reducing the *U*/*f* ratio, which reduces the rotor losses. Lower *U*/*f* ratio means also that the stator reactive power increases, since the magnetisation from the rotor side is decreased.

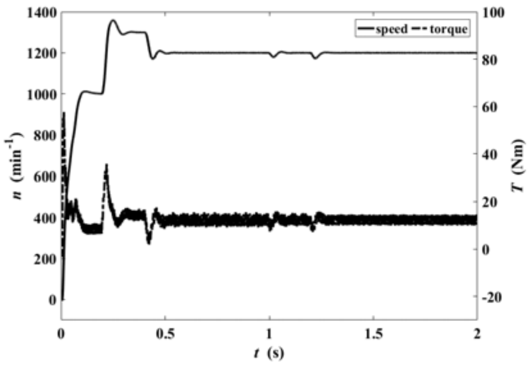

Fig. 14. Speed and torque of a DFIM driving a fan with smooth transitions of the rotor voltage

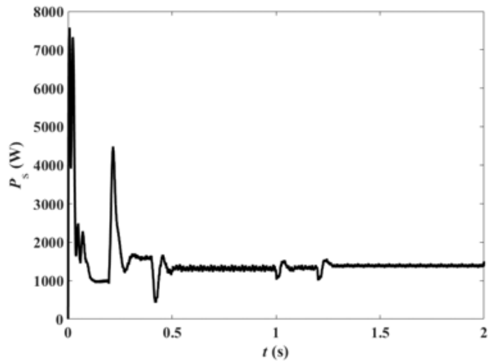

Fig. 15. Stator active power

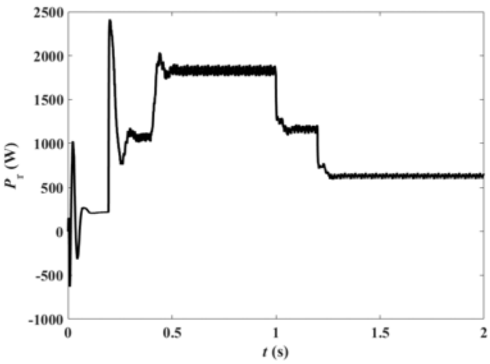

Fig. 16. Rotor active power

Conclusion

In the study, it has been shown that DFIM can be used as a driving motor in the drives, which operate in the limited area above the synchronous speed, using simple scalar open-loop control for the rotor supply. The machine is able to self-synchronise. In case of sudden large torque changes, the synchronisation may be lost, but it can be retrieved again.

The advantages of the presented DFIM drive system are its simplicity, robustness, accurate rotor speed as well as low frequency and power rating of the rotor voltage source.

The main disadvantages of the drive system are slip rings due to their maintenance and possibility of synchronisation loss, if sudden large load torque occurs.

The *U*/*f* control algorithm with the smooth voltage and frequency transitions has to be integrated in order to avoid large torque shock. Also, the algorithm has to be able to find the proper *U*/*f* ratio in order to reduce the input power and increase efficiency as much as possible, while maintaining the stable operation.

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