ZESZYTY NAUKOWE POLITECHNIKI ŚLĄSKIEJ 2004
Seria: ELEKTRYKA z. 193 Nr kol. 1640

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EXAMINATIONS OF SYNCHRONOUS PARASITIC TORQUES IN DOUBLE-SPEED, SQUIRREL-CAGE INDUCTION MOTORS

Summary. In double-speed induction machines phenomenon of parasitic torques is being enlarged as compared to one-speed machines. This is why such motors should be specially designed and higher harmonics must be considered in design process. Using computer simulations allows to reduce costs of designing of new machines and saves a lot of time. Simulation results, however not quite adequate, allow to examine machine before it is built. It can be very helpful tool in designer's hand. However only full theoretical end practical measurements allow to get full information about explored machine. Problem of parasitic torques in double-speed induction motor is still vivid and studies on this topic should be continued.

BADANIA SYNCHRONICZNYCH MOMENTÓW PASOŻYTNICZYCH W DWUBIEGOWYCH MASZYNACH INDUKCYJNYCH KLATKOWYCH

Streszczenie. Zjawiska pasożytnicze w indukcyjnych maszynach dwubiegowych występują wyraźniej niż w jednobiegowych. Z tego powodu podczas procesu projektowania maszyn wielobiegowych nie można pomijać oddziaływania wyższych harmonicznych przestrzennych przepływu. Wykorzystanie symulacji komputerowej modeli matematycznych maszyn pozwala na skrócenie procesu projektowania i redukcje kosztów. Wyniki symulacji, choć nie do końca dokładne, pozwalają zbadać zachowanie prototypu zanim zostanie wykonany. Jednak dopiero pełme badania pomiarowo-symulacyjne pozwalają na uzyskanie dokładnych informacji o badanej maszynie. Problem momentów pasożytniczych w indukcyjnych silnikach wielobiegowych jest nadal żywy i badania w tej dziedzinie powinny być kontynuowane.

1. INTRODUCTION

Induction motors are frequently used because of their simplicity and a low price. In all induction motors there is a phenomenon of appearing of parasitic torques connected with different parameters of machine [1, 2]. Some of them are connected with reluctance of magnetic circuit while others are connected with higher space harmonics of magnetic flux.

In the second case asynchronous and synchronous torques are generated. Both are deforming natural curve of induction machine causing a lot of unfavourable symptoms like noise, vibrations and difficulties with start. There are some ways of reducing these torques like selection of number of rotor's and stator's slots or skew cage with additional ring in rotor. Synchronous parasitic torques occur in classes connected with their synchronous speeds. Properly selected parameters allow to reduce one class of parasitic torques.

Sometimes, if it is a need to obtain two rotating speeds in the same machine, the double-speed induction motor can be used. In such a motor there are two windings or one switchable winding allowing for step change of number of poles depending on type of connection. In double-speed motor there are more classes of parasitic torques and it is difficult to select optimal number of slots. Optimal number of slots for one connection is worse for another.

2. NATURE OF PHENOMENON

Synchronous torques are formed in air gap as a result of cooperation between higher space harmonics of stator and rotor windings. Paths of generating synchronous torques can be easily analyzed using diagram of decomposition of induction machine into elementary machines [1, 2, 3]. This phenomenon will be explained on the example double speed, squirrel-cage, induction motor Sg132S4-2. Diagrams of decomposition of the machine into elementary machines, with some paths of generating of synchronous torques, are shown in figure 1 (for number of poles p=1) and in figure 2 (for p=2). Synchronous torque appears where there are two elementary machines in stator and two in the same columns in rotor (when any rectangle can be constructed).By analogy to synchronous machine one of this elementary machines is called exciting machine and second – synchronous machine. In other words there are always two harmonics taking part in generating of synchronous torque. In following figures there are shown some possible paths of generating of synchronous torques taking into account first rows of rotors diagrams of decomposition for each type of connection.

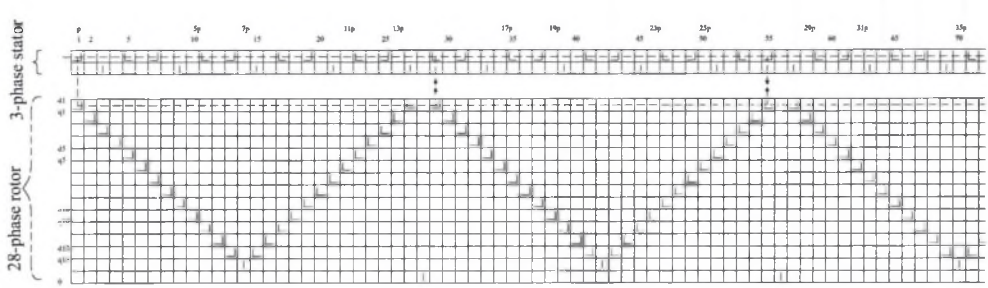

Fig.1. Diagram of decomposition of machine with some paths of generating of synchronous torques; Qs=36, Qr=28, 2p=2

Rys.1. Schemat rozkładu na maszyny elementarne z torami generowania momentów synchronicznych; Qs=36, Qr=28, 2p=2

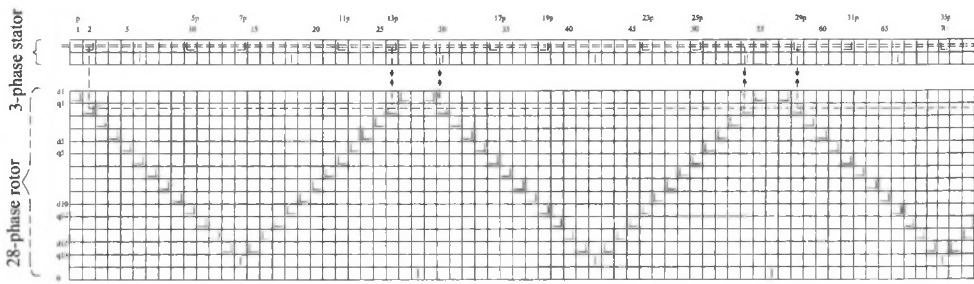

Fig.2. Diagram of decomposition of machine with some paths of generating of synchronous torques; Qs=36, Qr=28, 2p=4

Rys.2. Schemat rozkładu na maszyny elementarne z torami generowania momentów synchronicznych; Qs=36, Qr=28, 2p=4

According to orientation of axes of elementary windings in exciting and in synchronous machines, synchronous torque can have different synchronous speed and different period of parasitic synchronous torque-angle curve. Following table shows synchronous speeds of parasitic torques existing in examined machine.

Table 1

Synchronous speeds for different machine's speeds

synchronous speeds	brake	stopped rotor	machine
I speed p=2- n_n=1445 [rpm]	-107,14	0	214,29 53,57
II speed p=1- n_n=2895 [rpm]	-214,29 -53,57	0	107,14

It can be noticed that at each of two possible connections generated parasitic torques have different synchronous speeds, and general number of generated parasitic torques seems to be doubled. The reason of this is that at every connection type windings generate different harmonics (compare fig.1. and fig.2.).

3. MATHEMATICAL MODEL

Mathematical model of examined double-speed induction machine consists of two independent parts [4]. Every part describes one of possible connections. Double-speed machine is considered as two single-speed machines with the same parameters (equivalent to real machine) placed on the same shaft and run alternately. This model was created using following simplifying assumptions:

- → magnetic circuit is linear,
- → windings are symmetrical and discrete,
- → air-gap is smooth and even,
- → current density along slots is constant,
- → only radial component of magnetic field is considered

This model is given in co-ordinates α,β and d,q with following equations:

$$\left[u_s^{\alpha\beta}\right]=\left[R_s^{\alpha\beta}\right]\left[i_s^{\alpha\beta}\right]+\left[L_{\sigma s}^{\alpha\beta}\right]\frac{d}{dt}\left[i_s^{\alpha\beta}\right]+\left[M_{ss}^{\alpha\beta}\right]\frac{d}{dt}\left[i_s^{\alpha\beta}\right]+\frac{d}{dt}\left(\left[M_{sr}^{\alpha\beta dq}(\vartheta)\right]\left[i_r^{dq}\right]\right),$$

$$\left[0\right]=\left[R_r^{dq}\right]\left[i_r^{dq}\right]+\left[L_{\sigma r}^{dq}\right]\frac{d}{dt}\left[i_r^{dq}\right]+\frac{d}{dt}\left(\left[M_{rs}^{\alpha\beta dq}(\vartheta)\right]\left[i_s^{\alpha\beta}\right]\right)+\left[M_{rr}^{dq}\right]\frac{d}{dt}\left[i_r^{dq}\right], \tag{1}$$

$$J\frac{d\Omega_m}{dt}=T_e-T_m, \tag{2}$$

$$T_e=\sum_{\nu=1,2,3\ldots}T_{e\nu}=\sum_{\nu=1,2,3\ldots}\left[i_s^{\alpha\beta}\right]^T\frac{\partial}{\partial\vartheta}\left[M_{sr\nu}^{\alpha\beta dq}(\vartheta)\right]\left[i_r^{dq}\right], \tag{3}$$

where:

$\left[u_s^{\alpha\beta}\right]$ - vector of stator voltage in α,β terms,

$\left[i_s^{\alpha\beta}\right],\left[i_r^{dq}\right]$ - vectors of stator and rotor currents in α,β and d,q terms,

$\left[R_s^{\alpha\beta}\right],\left[R_r^{dq}\right]$ - matrixes of resistance of stator and rotor in α,β and d,q terms,

$\left[L_{\sigma s}^{\alpha\beta}\right],\left[L_{\sigma r}^{dq}\right]$ - matrixes of leakage inductances in α,β and d,q terms,

$\left[M_{ss}^{\alpha\beta}\right],\left[M_{rr}^{dq}\right]$ - matrixes of self-inductances in α,β and d,q terms,

$\left[M_{sr}^{\alpha\beta dq}(\vartheta)\right],\left[M_{rs}^{\alpha\beta dq}(\vartheta)\right]$ - matrixes of mutual inductances: stator-rotor, rotor-stator,

J - moment of inertia,

T_m - load torque,

ϑ - angle of rotor rotation,

T_e - electromagnetic torque,

Ω_m - rotor angular speed.

Of course mathematical model can not consists of all harmonics, and it is not necessary because when taking into account only main electromagnetic torque and some dominating parasitic torques allow to get good analogy to real curves. To select dominating space harmonics we must know the diagram of decomposition of our 3-phase squirrel-cage machine into elementary machines (Fig.1. and Fig.2.) and a table of factors [8] calculated for harmonics pairs according to following equation:

$$k_{(\nu,\rho)} = \frac{k_{ws\nu} \cdot k_{ws\rho} \cdot k_{wr\nu} \cdot k_{wr\rho}}{\nu \cdot \rho \cdot n}, \tag{4}$$

where:

$k_{ws\nu}$, $k_{wr\nu}$ – stator and rotor windings factors for ν harmonic,
$k_{ws\rho}$, $k_{wr\rho}$ – stator and rotor windings factors for ρ harmonic,
n – row occupied by harmonics ν, ρ in diagram of decomposition.

Table 2

Factors of harmonics generating synchronous torques in first rows of diagrams of decomposition

Pair of harmonics	K factor multiplied by 100000	Synchronous speed [rad/s]
	p=1	
1;29	3,00	-22,44
1;55	0,91	11,22
1;83	0,73	0
1;85	0,65	0
	p=2	
2;110	10,37	5,61
2;26	9,94	22,44
2;58	3,63	-11,22
2;82	3,15	0
2;86	2,45	0
26;110	0,18	0

The factor says which parasitic torque is stronger and has higher amplitude. The table also shows synchronous speeds of generated torques. It is easy to notice that for p=1 dominating synchronous torque appears during brake work while for p=2 most dominating torques occur during motor work. This can be observed in following figures presenting results of computer simulations of described model [5]. The model takes into account only harmonics from the first row of rotor's diagram of decomposition. So simulation results are different from measurement results because model is simplified to only a few harmonics, but some trends are easily visible.

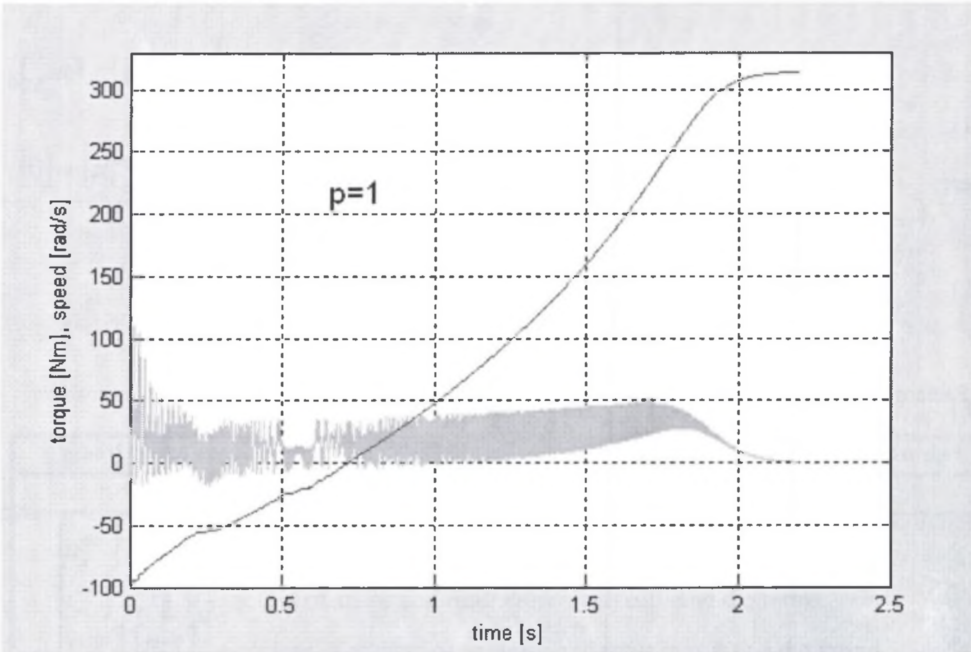

Fig.3. Simulation results (speed, and torque time functions) for p=1
Rys.3. Wyniki symulacji (prędkość i moment w funkcji czasu) dla p=1

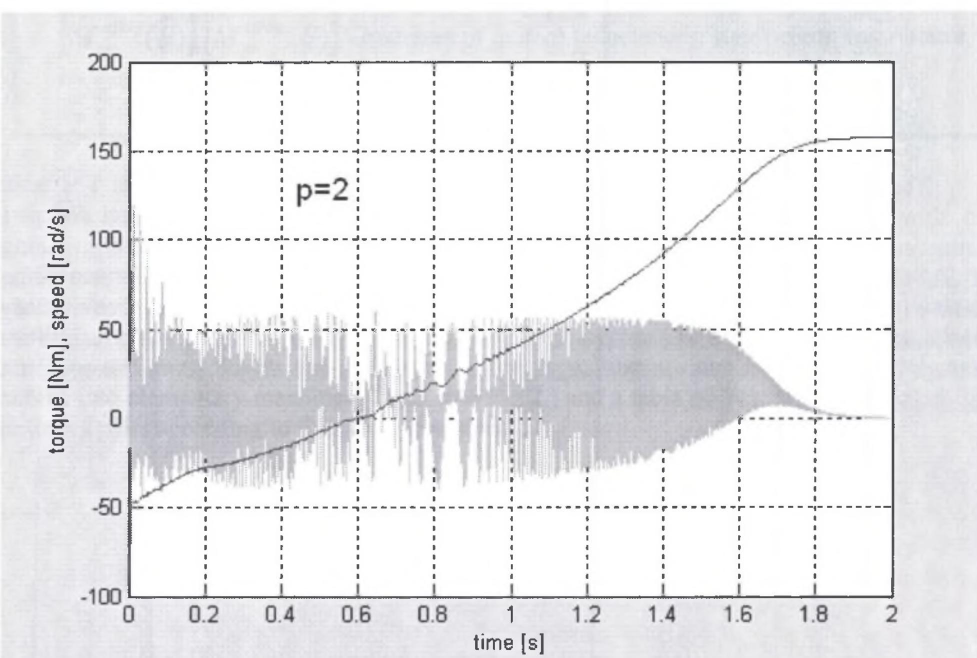

Fig.4. Simulation results (speed, and torque time functions) for p=2
Rys.4. Wyniki symulacji (prędkość i moment w funkcji czasu) dla p=2

4. MEASURING STAND

Measuring stand is shown in fig.5. It consists of examined machine (up to 132 mm of shaft high) coupled with Hottinger torquemeter. The torquemeter measures torque on shaft and rotational speed of rotating parts. Signals are obtained and filtered by Hottinger torquemeter and then recorded using 4-channel oscilloscope Tectronics. At the end of shaft there are two plates, which allow to place additional mass. In this way general moment of inertia can be increased. Increased moment of inertia allows to extend accelerating time and then parasitic phenomenon can be observed more accurately. At the end of the shaft, just behind additional mass, there is a space for coupling of additional machine. It can be another AC or DC machine loading examined one.

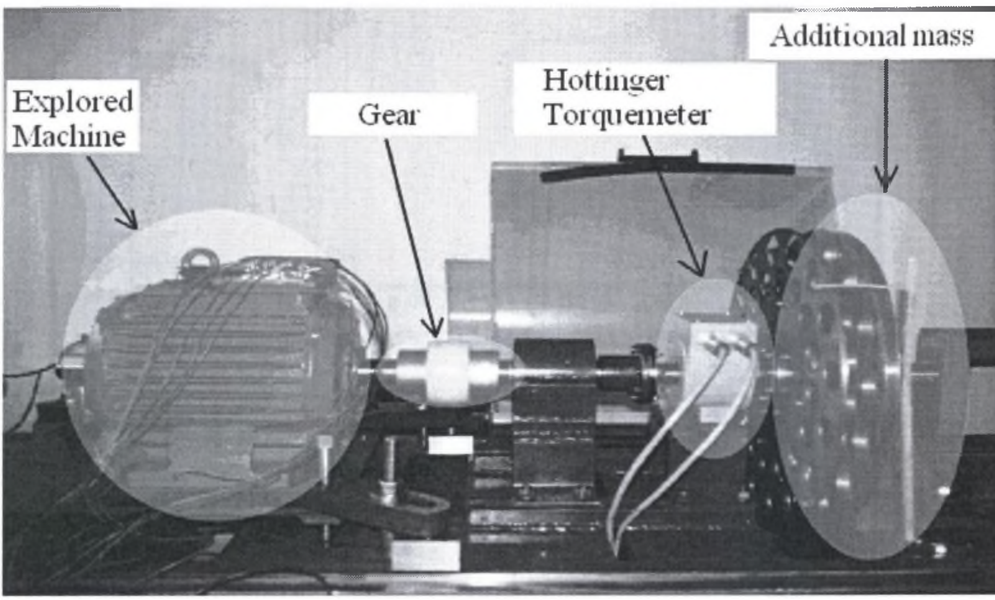

Fig.5. Measuring stand
Rys.5. Stanowisko pomiarowe

Following pictures show start and change of direction of examined machine for both types of connection (both number of pole pairs p=1 and p=2). Recorded curves present rotational speed and torque on shaft of motor [7].

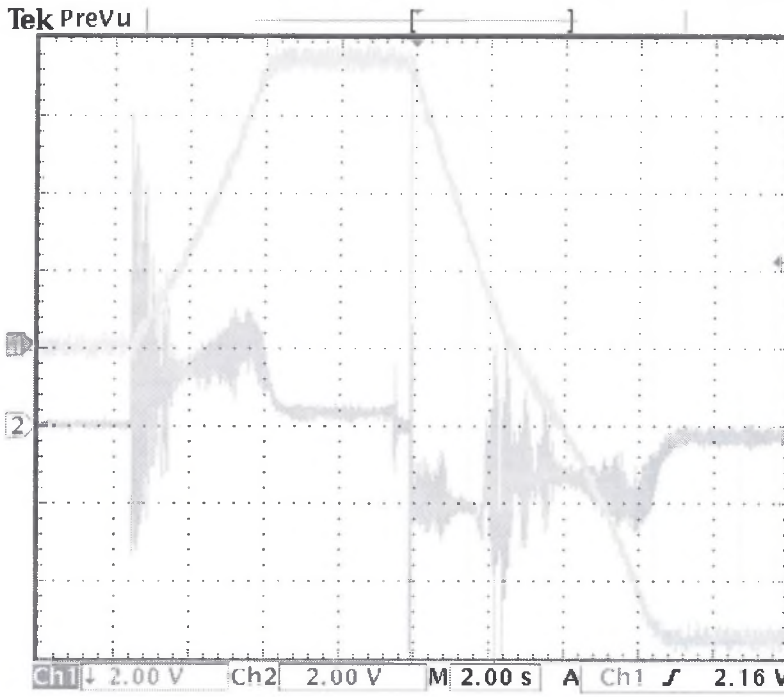

Fig.6. Measuring results for p=1 (start and change of direction)
Rys.6. Wyniki pomiarów dla p=1 (rozruch i nawrót)

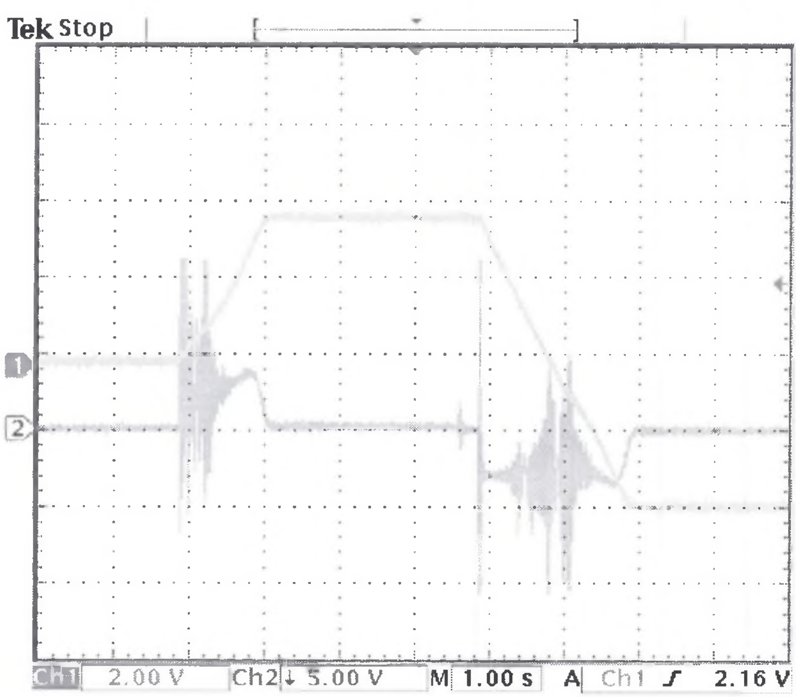

Fig.7. Measuring results for p=2 (start and change of direction)
Rys.7. Wyniki pomiarów dla p=2 (rozruch i nawrót)

Sometimes parasitic torque causes that start of engine is interrupted and it works as a synchronous machine with rotational speed of this parasitic torque. In properly constructed machines it becomes rarely and usually during hard start with large load. Machine cannot work for a long time in this state because of current bigger then rated. Laboratory measurements were performed using special rotors where parasitic torques are intentionally enlarged, and it was easier to obtain synchronization of machine. Such a state is shown in figure 8. The machine is starting and then, caught by first synchronous torque, it is working as a synchronous machine.

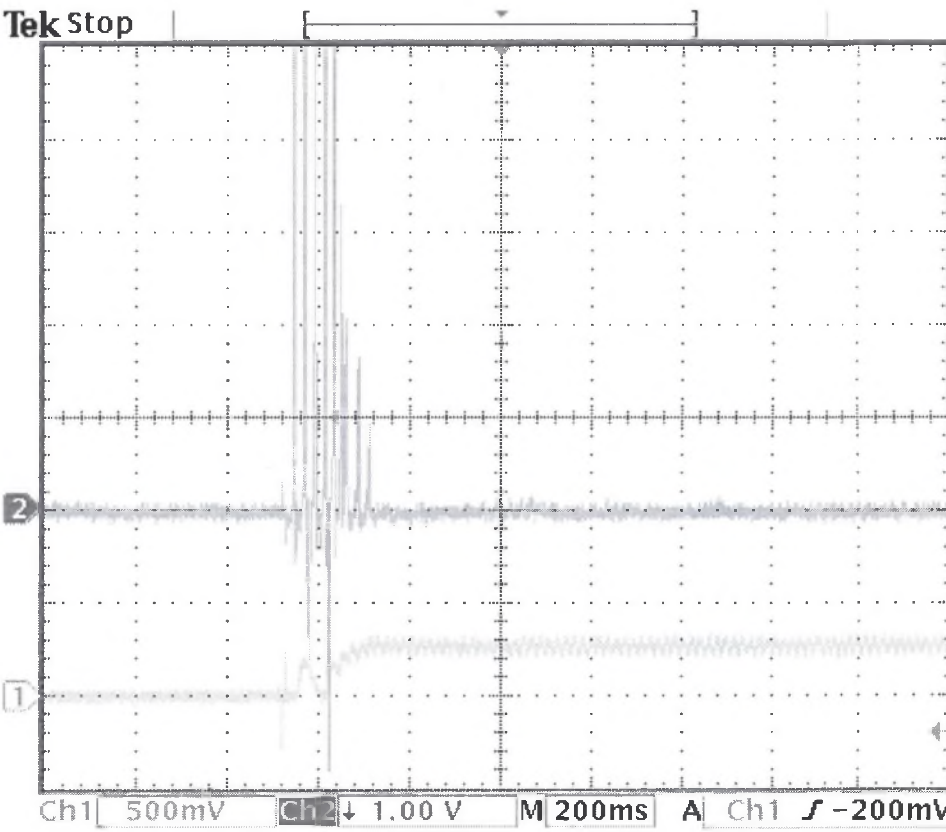

Fig.8. Synchronization of machine during start
Rys.8. Synchronizacja podczas rozruchu

5. CONCLUSIONS

Because of enlarged number of parasitic torques existing in multi-speed, squirrel-cage induction machines they cannot be omitted during design process. Creation of mathematical model and simulation examining of machine has a lot of advantages. It allow to reduce time and cost needed for prototype building. Having ready mathematical model it is very easy and quick to examine different variants of the same machine. However simulating results are not 100% accurate, they are sufficient for selecting worse and better options. Conducted studies prove that simulation results are convergent with measurement results, and that simulations can be very helpful for designers [6].

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Wpłynęło do Redakcji dnia 14 maja 2004 r.