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THE TORQUE MEASUREMENT BASED ON VARIOUS PRINCIPLES*)

ABSTRACT *Torque measurement under fast transient phenomena of the electrical machines is sometimes a serious problem. The squirrel cage asynchronous machine is the most used electrical machine in the industry, very often together with the frequency converter. Therefore the main attention is paid to this machine. The aim of this work is to use various methods of torque measurement on the same machine and to compare the obtained results.*

Some methods need either a special intervention to the machine under the test or expensive equipment. Due to this fact these methods are applicable almost exclusively in the laboratory. Nevertheless, they would give important results.

As a contrast, some methods need just a speed sensor, current sensors or helping measurement turns. The speed or current sensors can be used for other purposes simultaneously. These methods are very suitable for industry.

Finally, we choose some suitable transient phenomena (run-up, reversal operation,…) and we will analyse the torque by each different method. For a complete description, this paper contains the short overview of all, well known methods:

- *Mathematical Simulation*
- *Mathematical calculation based on mutual flux measurement*
- *The dynamometer measurement*
- *The torsion torque transducer*
- *Methods of determination of torque curve (run-up method)*
- *Rotary contactless accelerometer*
- *Torque measurement with the help of piezoelectric accelerometers*

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The aim of this submission is to describe some suitable methods for torque measurement. The choice of the suitable method of measurement depends on the actual situation, equipment and instruments that are at the hand.

This work has been supported by the project MSM 232200008.

1. INTRODUCTION

Normally the performance of rotating drives is described by torque and rotational speed. In electrical machine practice we need a method of measuring acceleration (or speed) and torque under widely different conditions. Measuring of the rotational speed can be done accurately in many cases. The torque measurement requires suitable equipment which is sometimes very expensive.

It is possible to say that the following methods, which will be mentioned here, are valid generally but some methods are designed especially for asynchronous machine torque measurement.

The squirrel cage asynchronous machine is the most used electrical machine in the industry, very often together with the frequency converter. Therefore the main attention is paid to this machine.

The aim of this work is to use various methods of torque measurement on the same machine and to compare the obtained results. The methods of measurement could be divided into two groups.

Some methods need either a special intervention to the machine under the test or expensive equipment. Due to this fact these methods are applicable almost exclusively in the laboratory. Nevertheless, they would give important results.

As a contrast, some methods need just a speed sensor, current sensors or helping measurement turns. The speed or current sensors can be used for other purposes simultaneously. These methods are very suitable for industry.

Finally, we choose some suitable transient phenomena (run-up, reversing,…) and we will analyse the torque by each different method. For a complete description, this paper contains the short overview of all, well known methods. The attention is paid to the latest case – the proposal of the torque measurement thanks to piezoelectric accelerometers.

2. MATHEMATICAL SIMULATION

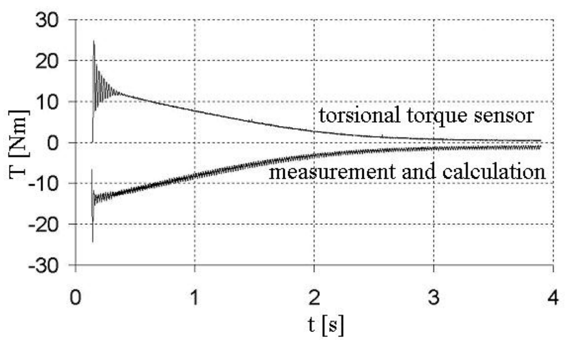
The mathematical model is mentioned here just for the sake of complexity. Several scientific books and research papers are devoted to the mathematical model. The basic mathematical model is very well known and the electrical and mechanical magnitudes as well can be easy calculated. Nevertheless, the mathematical model contains certain simplifications, i.e. the slot effect, magnetic circuit losses or skin-effect in rotor aluminium bars is neglected. Especially during the transient phenomena these simplifications could be the cause of significant differences between mathematical model and reality. In this respect, the experiment is irreplaceable.

3. MATHEMATICAL CALCULATION BASED ON MUTUAL FLUX MEASUREMENT

It is also possible to calculate the torque. This way is based on the instantaneous flux measurement. In the case of the asynchronous machine torque measurement we can replace the flux by the integration of the terminal voltage. The error, caused by neglecting the voltage drop on the winding resistivity, is small in the first approach. A better solution is to add the special helping turn into the main winding. Then we can calculate the torque with the help of relation

$$T_e = \frac{2}{3\sqrt{3}}\left[\psi_a\left(i_b - i_c\right) + \psi_b\left(i_c - i_a\right) + \psi_c\left(i_a - i_b\right)\right] \quad (1)$$

a)



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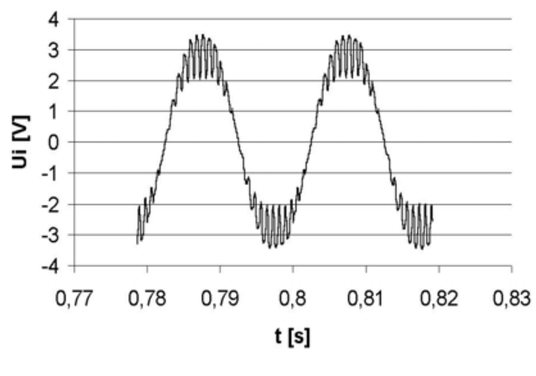


Fig.1.
a) Run-up of the asynchronous machine (low voltage, special rotor, the sign is wittingly opposite). b) The helping turns voltage. We can see the slots effect. c) The calculated torque. The calculation is based on the integration of stator voltage terminals.

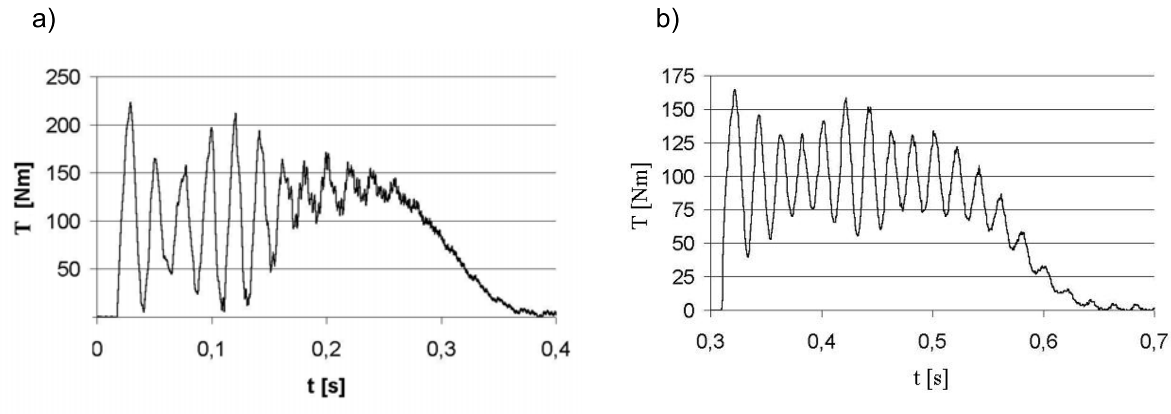


Fig.2. The calculated torque. The calculation is based on the integration of:
a) helping turn voltage (stator resistivity is neglected), b) stator voltage terminals.

The special helping turn in the slots must be situated as near to the air gap as possible. The reason is based on the rule that the leakage flux has no influence on the torque. Consequently, the leakage flux can not be detected by the helping turn.

This solution is quite precise but requires a specially adapted machine. If we use the first mentioned possibility, we can apply this way on any asynchronous machine, but the accuracy is little bit lower.

4. THE DYNAMOMETER MEASUREMENT

In this case of measurement, the stator of the dynamo has no fixing shoes but the stator can swing round. With the help of spring and arm of the well known length we can measure the stator reaction of torque which is produced on the rotor.

In this case we also have several possibilities and variability. The torque-dynamometer could be

- a DC machine,
- an AC machine + frequency converter,
- an eddy current machine,
- or powder-brake machine.

The measurement device could be made not only of a spring but also of the piezoelectric sensor or any another press or force sensor, etc.

5. THE TORSION TORQUE TRANSDUCER

The principle is based on torsion part of shaft and its torsion. Measurement of torsion of the shaft is possible in several ways.

a) b)

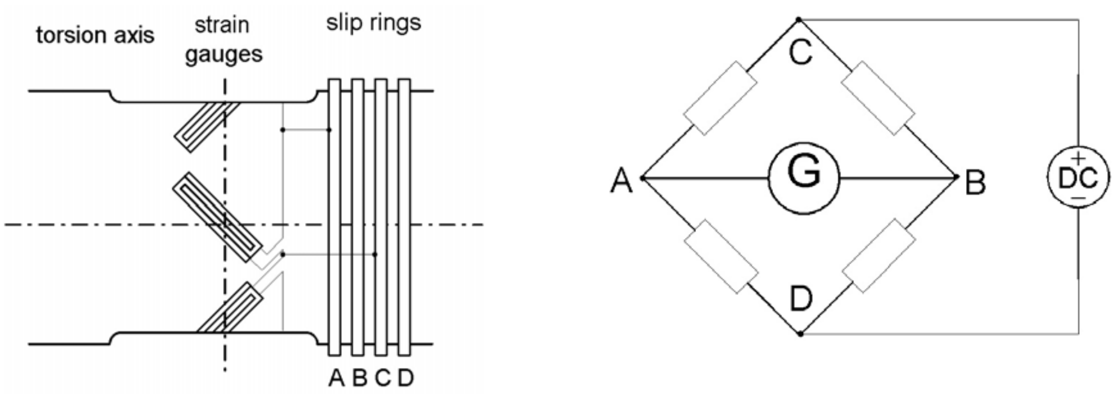


Fig.3. Measurement of torque with the help of strain gauges (four gauges in full bridge arrangement)

For a torque measurement, we must place these strain gauges in this way. For pressure, tension and bending measurement the position of strain gauges are different. For the transfer of the signal from moving rotor to stator terminals, the slip rings are used. In this way, the signal is partly interfered. It is also possible to use instead of slip rings the special contacts with mercury or contactless telemetry data transfer.

Otherwise, the torsion of the measurement torsion shaft is transferred to a phase shift of the impulses. These impulses should be produced by optical, magnetic or another suitable type of sensors.

6. METHODS OF DETERMINATION OF TORQUE CURVE

We can determine the torque characteristic of asynchronous machine by loading with the help of some of the previously mentioned methods. However, this way is time and energy consuming.

We must set several value of loading, i.e. points of torque curve. When the slip is increasing, we must solve additional problems, like the over-current, thermal stress, etc.

Another way is to derive the torque characteristic from the run-up characteristic. If the run-up of the machine is retarded, we can determine the static torque curve instead of dynamic torque curve. Both these characteristic could be very different. The retardation can be made by lower voltage instead of the nominal voltage or additional moment of inertia on the shaft.

During the run-up of the asynchronous machine the slip is changing from 1 to 0 (zero) and the machine must go through every point of torque characteristic. The following equation is valid, when the machine is unloaded and the mechanical losses are neglected:

$$T = \frac{d\omega}{dt} \tag{2}$$

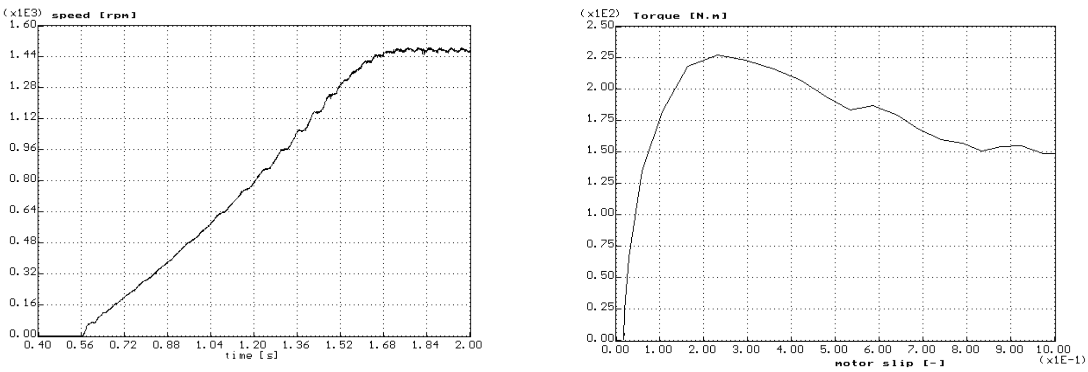


Fig.4. Run-up of the asynchronous machine and its derivation – the torque as dependent on the slip

During the run-up we must measure the speed as dependent on time and then mathematically derive it. This could be a serious problem. Electrical derivation during the run-up is also possible as well.

7. ROTARY CONTACTLESS ACCELEROMETER

The torque measurement with the help of accelerometer is based on this equation. If we measure in principle the acceleration instead of speed, we need not to derive the speed signal and we have directly (after multiplying by the moment of inertia of course) the torque signal.

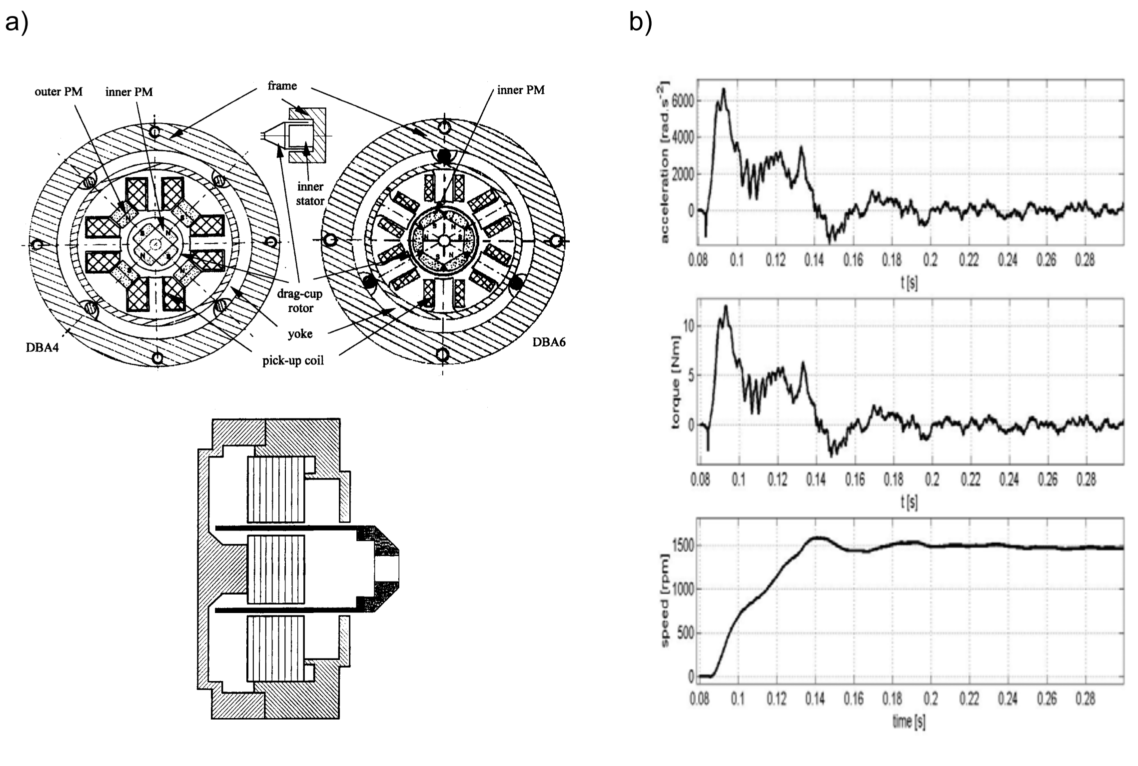


Fig.5.
a)Schematic view of angular acceleration sensor: 4-pole sensor, 6-pole sensor, cross section, b) accelerometer's measured signal and evaluated torque and speed as dependent on time

For this purpose contactless acceleration sensors based on the Ferraris principle are very suitable. With this sensor, highly dynamic signals proportional to the change of speed are available, even at standstill.

8. TORQUE MEASUREMENT WITH THE HELP OF PIEZOELECTRIC ACCELEROMETERS

Piezoelectric accelerometer is a sensor, whose signal is proportional to the acceleration. For these purposes we choose the sensor which is sensitive in one direction only. These sensors are placed on the stator of the asynchronous machine. The stator can swing round thanks to the additional bearings.

The additional bearings are fixed in the helping end-shield. In this way the rotor has to be equipped with a special extended shaft. Otherwise it could be impossible to connect the coupling and loading machine. Also the fan on the shaft was removed.

The first helping end-shield is fixed to the main frame. The second helping end-shield must be fixed through a spring element. This is suitable for balancing the manufacturing tolerance, thermal expansion, etc. The first fixing end-shield prevents the stator from any different movement but waving. In this case the one piezoelectric accelerometer is sufficient for measuring the reaction of the stator.

If we fix both helping end-shields via spring element, the stator is hanging and completely released for movement in any direction. In this case we need at least two piezoelectric sensors to determine the reaction movement in general direction. The movement in shaft direction usually can be neglected.

We can change the position and orientation of accelerometers. Fig. X represents the orientation for stator's rotary movement, Fig. Y represents the stator's shift in one (specified) direction and Fig. Z shows the accelerometer's position for general jump of the machine in the XY-plane.

Each accelerometer sensors is placed on a special truckstone. These truckstones allowed us to change the sensor orientation by about 90 deg. The whole truckstone together with sensor allowed us to change the orientation with respect to the stator of the dynamometer by about ± 30 deg. In this way the accelerometer can take almost any orientation in surface *xy*.

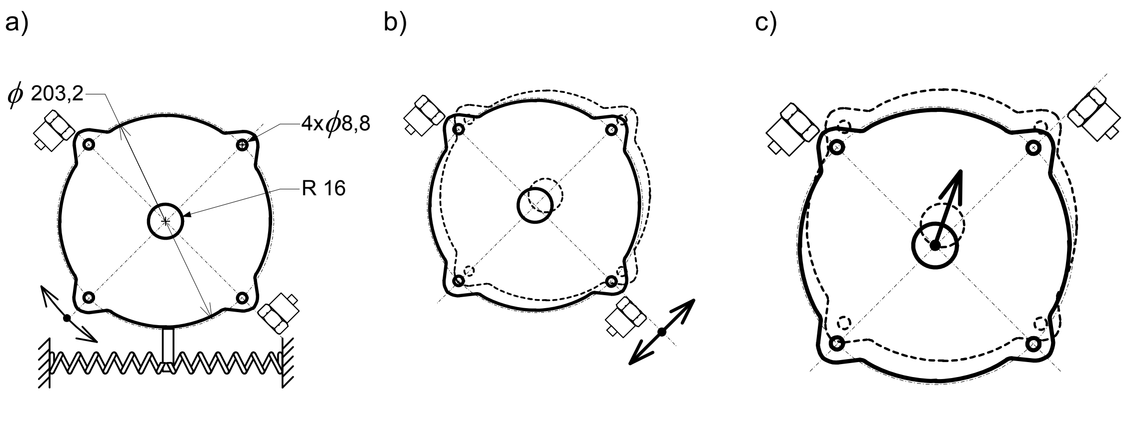
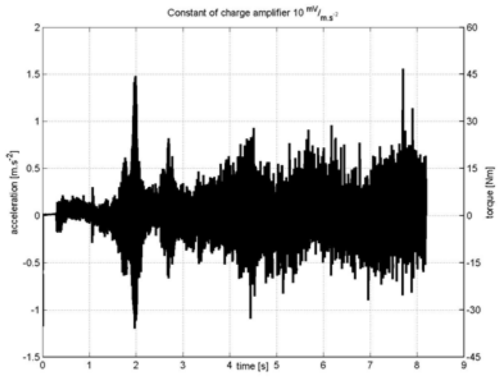


Fig. 6.
a) The accelerometers orientation for stator's rotary movement, b) the stator's shift in one (specified) direction, c) the accelerometer's position for general jump of the machine in the XY-plane

In future, the dynamometer will be further equipped by a rotary contactless accelerometer, helping turns for mutual flux measurement, rotor and stator incremental sensor and current and voltage transducers as well.

a)



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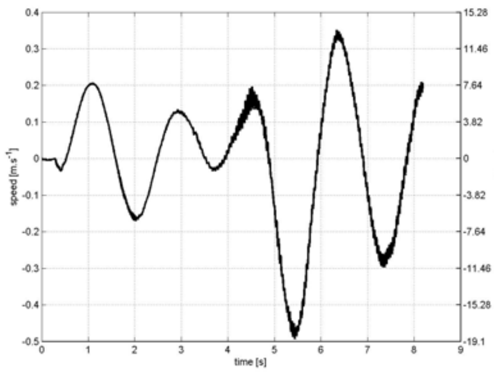

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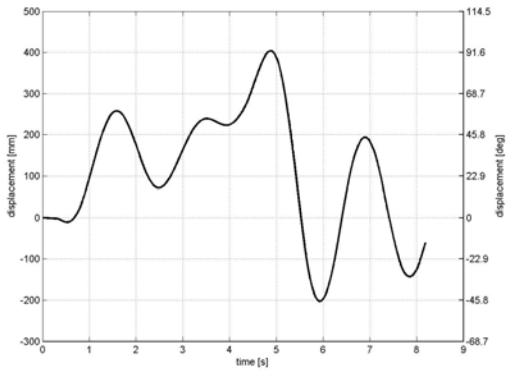

Fig.7.
a) The accelerometer signal, b) The speed signal, c) Displacement (torque) of the stator

9. REMARKS AND CONCLUSION

The aim of this submission is to describe some suitable methods for torque measurement. The choice of the suitable method of measurement depends on the actual situation, equipment and instruments that are at the hand.

The asynchronous dynamometer is supplied by a frequency converter. In this way it should work in the motor as well as the generator mode. The mechanical load will be connected through the Cardan shaft. Thanks to this special shaft the torque can be periodically changed during one revolution. In this way we can replace the mechanical load of the piston-engine-type by the electrical rotary machine. The rotor of the dynamometer is exchangeable. We can use the classical squirrel cage rotor, squirrel cage rotor with defected bar or defected short circuited ring etc.

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POMIAR MOMENTU W OPARCIU O RÓŻNE ZASADY

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STRESZCZENIE *Pomiar momentu przy szybkich nieustalonych stanach w maszynach elektrycznych bywa poważnym problemem. Maszyna asynchroniczna z wirnikiem klatkowym jest najczęściej używaną maszyną w przemyśle, bardzo często wraz z przetwornikiem częstotliwości. Dlatego też główną uwagę zwrócono na tę maszynę.*

Celem tej pracy było zastosowanie różnych metod pomiaru momentu tej samej maszyny i porównanie uzyskanych wyników.

Niektóre metody wymagają dokonania specjalnego zabiegu w badanej maszynie lub drogiego wyposażenia. Z tego powodu metody te nadają się do zastosowania wyłącznie w laboratorium. Tym niemniej zapewniają one uzyskiwanie ważnych wyników.

Przeciwnie, niektóre metody wymagają tylko czujnika prędkości, czujników prądu lub pomocniczych zwojów pomiarowych. Czujniki prędkości lub prądu mogą być równocześnie wykorzystywane do innych celów. Takie metody są bardzo odpowiednie dla przemysłu.

Ponadto wybieramy pewne odpowiednie zjawiska nieustalone w stanach przejściowych (rozbieg, praca nawrotna) i będziemy analizowali moment każdą metodą. Z troski o kompletność opinii praca zawiera krótki opis wszystkich znanych metod:

- *Symulacja matematyczna*
- *Obliczanie matematyczne oparte o pomiar strumienia głównego*
- *Pomiar dynamometryczny*

- *Czujnik momentu skrętnego*
- *Metody oparte o wyznaczenie krzywej momentu (metoda rozbiegu)*
- *Bezzestykowy akcelerometr obrotowy*
- *Pomiar momentu za pomocą akcelerometrów piezoelektrycznych.*

Celem przedstawionej pracy jest opis metod nadających się do pomiaru momentu. Wybór odpowiedniej metody pomiaru zależy od aktualnej sytuacji, wyposażenia i od przyrządów będących do dyspozycji.