

# Detecting Incipient Stator Winding Conductor Faults in Inverter Fed Machines

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## Keywords

«Adjustable speed drive», «Diagnostics», «Induction motor», «Maintenance»

## Abstract

In variable speed drive applications the inverter fed induction machine is one of the most reliable systems. However, increasing demands on efficiency leads to higher wear of all system components. Unexpected machine breakdowns cause economic losses and/or undesired scenarios in safety-critical areas. Thus condition monitoring of all components can reduce the risk of outages due to faults. High electrical and magnetic forces together with increased environmental stresses in rough application fields lead to a higher probability of stator winding faults. Beside inter-turn short-circuit faults open-circuit winding faults are under the most frequent types of faults. Open-circuit winding faults usually start with a crack or conductor deformation. Thus the resistance in the corresponding stator winding phase is increased. Detecting such faults already in an early stage provides the possibility to react timely before a more severe fault occurs. This work presents a method to detect open-circuit winding-faults in an early stage without additional hardware. The method is based on the identification of the phase resistance by combination of measured current reaction to different voltage steps. A specific signal processing chain supplies a fault indicator able to detect the fault by magnitude and position.

## Introduction

In the past decades a lot of work has been done focusing condition monitoring of electrical machines. Basically, the main machine-breakdown-causing faults can be classified into stator, rotor and bearing related faults [1]-[2]. Stator winding faults are considered one of the most frequent class with a rate of 30-40%. Within the stator related fault class open-circuit winding together with short-circuit winding faults are the dominating cases [3]. Continuous monitoring of the machine windings is necessary to ensure a detection of a fault in an early stage. This provides the possibility to react timely on a defect without the risk of a sudden breakdown.

The main reasons for stator winding faults are thermal, electrical, mechanical and environmental stress. Considering drive systems in rough areas it is clear that they are more prone to failure due to higher environmental stresses. Operation of an electrical machine in a traction system lead to increased stress on the stator windings due to high acceleration/breaking forces, extreme temperature cycles, high vibrations, debris etc. All these effects can lead to increased wear and finally to failure of the winding system.

As one of the consequences cracks may develop in stator winding conductors finally leading to open-circuit winding faults or in case of thermal damaged isolation even ending up in short circuit. But not

only cracks, also conductor deformations can cause an increased resistance and thus higher losses. Both effects lead to an increased resistance value and the damaged area is possibly heated up to critical temperature ranges. Hence, an undetected incipient open-circuit winding fault can lead to severe machine failures also involving other machine parts and the risk of a breakdown.

By detecting such fault scenarios already in a very early stage a proper and timely reaction can be realized avoiding unexpected outage of the machine. A fault-tolerant control algorithm can be started or the maintenance work period can be scheduled. This can prevent from complete destruction of the machine as only the stator winding has to be investigated and/or replaced. Applying a fault detection method in the drive system without the need of special external equipment leads to decreased maintenance efforts. Monitoring sequences can be carried out periodically and the knowledge of machine state is accessible during operation without the need of high maintenance frequency or additional sensors and evaluation systems.

An open-circuit winding fault frequently starts with an increased stator winding resistance in the corresponding phase. As a consequence, the stator resistance will change with respect to the healthy case asymmetrically. Detecting such individual phase changes can provide information on the mentioned fault scenarios. Different methods can be found in literature dealing with stator resistance estimation. However, the methods are usually focused on temperature monitoring, improvement of control performance or the speed estimation [4]. Most methods [5]-[7], are developed for line fed drives and thus have reduced accuracy when applied to inverter fed drives. In [8] and [9] the stator resistance estimation is based on dc and zero-sequence injection for inverter-fed machines. All the published methods have shown adequate resistance estimation accuracy but are usually not related to fault detection. In this work a method is presented to detect developing open-circuit winding faults based on stator phase resistance estimation. The method is based on the current response of the machine due to voltage phasor steps. Basically, the main idea has already been investigated in [10] related to other fault conditions and based on the transient machine response. In the present paper the method is investigated for fundamental wave properties and in the steady state mode thus also the step duration is adapted. An outstanding advantage is given by the fact that no additional equipment is used but only the hardware present in a standard drive system (built-in current sensors). It must be stressed that the aim of the present paper is focused on the detection of incipient open-circuit stator winding faults. The method is not aimed to provide the possibility to detect also the stator resistance changes due to short-circuit faults.

## Stator Resistance and Fault Indicator

### Stator Resistance Estimation

Applying a voltage signal to the terminals of a system the current reaction provides information on system parameters. Assuming now the system to be composed of ohmic' materials and the voltage signal to be constant the current response will also be more or less constant. Resistors and wires as present in an electrical machine are ohmic' materials and the resistance can then be calculated by the relation  $r=u/i$  where  $u$  represents the voltage,  $i$  the current and  $r$  the resulting resistance value. Thus the resistance value can be calculated only by the knowledge of the applied voltage and the resulting current.

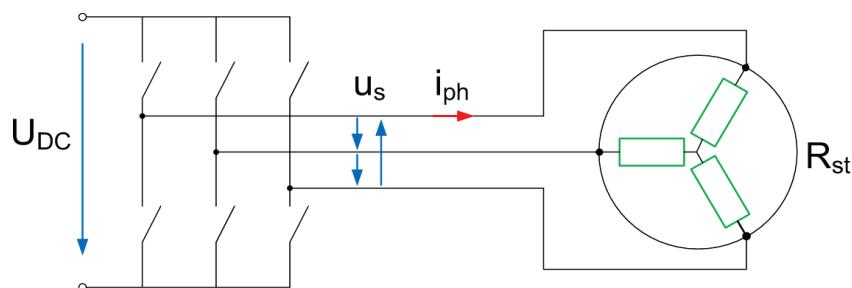


Fig 1: Three phase induction machine fed by a voltage source inverter

Considering now an inverter fed electrical machine (Fig 1) identification of stator winding resistance can be easily realized by applying the dc link voltage ( $U_{DC}$ ) through inverter switching to the machine's terminals and measuring the phase current ( $i_{ph}$ ) by the inverter built-in current sensors. The stator resistance  $R_{st}$  is then given by the voltage  $u_s$  applied to the machine terminals and phase current  $i_{ph}$ .

This voltage signal is composed of discrete pulses known as pulse width modulation (PWM). Thus it is disturbed and very difficult to identify accurately. Additionally, there are different phenomena arising from switching devices inherent characteristics such as power devices voltage drop, output voltage transitions slope, turn off/on time and the inverter interlock dead-time [10]-[13]. One possibility for identification is given by the usage of inverter output voltage sensors. But therefore three isolated voltage sensing circuits are required and usually not present in modern drive applications.

Using only the reference voltage of the control system to identify stator resistance will not provide accurate results. Hence, these disturbing effects must be eliminated or at least clearly reduced. Considering all inverter non-idealities the inverter dead-time and the power devices voltage drop have the highest impact on voltage distortion. Due to the fact that the dead-time and voltage drop are defined by hardware their influence can be clearly reduced by applying a special voltage pattern method when measuring the phase current and calculating the resistance value. However, it must be mentioned that the compensation procedure described in the following is a standard one for the elimination of the dead-time influence.

The proposed method consists of two measurements which are combined to reduce the mentioned disturbing influences. In a first step two voltage phasors are applied subsequently in one phase direction with different magnitudes (1). Within these steps the current reaction is measured and thus two current phasors are obtained.

Basically, the applied inverter output voltage can be split up into a reference part and a disturbing part. The disturbing part is influenced by the effects mentioned above, i.e. the inverter dead-time. The inverter dead-time is a preset hardware defined value. Practical power devices are known to need a finite time when changing states. To avoid short-circuit across the dc link by simultaneous active devices a delay has to be introduced before a device is turned on. The voltage distortion increases with switching frequency but not with applied voltage value. Thus it can be assumed that the disturbing part of the voltage signal is equal for both voltage steps and elimination can be realized by subtraction of both voltage steps (2).

$$\begin{aligned} \underline{u}_{S,1} &\rightarrow \underline{i}_{S,1} \\ \underline{u}_{S,2} &\rightarrow \underline{i}_{S,2} \end{aligned} \quad (1)$$

$$\begin{aligned} \Delta u &= u_{S,2} - u_{S,1} \\ \Delta i &= i_{S,2} - i_{S,1} \end{aligned} \quad (2)$$

$$r_s = \frac{\Delta u}{\Delta i} = \frac{u_{S,2} - u_{S,1}}{i_{S,2} - i_{S,1}} \quad (3)$$

Additional also a difference is calculated by the two current values. Now the resistance can be calculated by the differences from both values as given in (3). This obtained value represents an accurate estimate of the stator winding resistance corresponding to the phase direction of the active phase. For example, if the voltage phasor steps are applied into phase direction U also the resulting resistance value represents phase U. Due to the inverter-to-machine arrangement (stator winding connection) the calculated resistance includes also the resistances of the remaining phases but with reduced magnitude. However, these parts can be eliminated by a proper signal processing. The test and measurement procedure is repeated in each stator phase to identify the resistance with respect to all machine phases.

## Fault Indicator Generation

To get a clear impression of fault indicator generation procedure the signal processing chain is presented as a block diagram in Fig 2. At the beginning, a voltage phasor step (Phase U, Voltage Step 1) is applied in phase direction U and the corresponding current response is obtained (Phase U, Current Meas. 1). Subsequently a second voltage phasor step (Phase U, Voltage Step 2) is also applied with the same phase direction but with different magnitude and the corresponding current reaction is measured again (Phase U, Current Meas. 2). The current values obtained are forwarded to a resistance estimation block realized by (3). In the present work the voltage phasor was set to zero between each measurement. To reduce the measurement duration both voltage phasor steps can be applied immediately subsequent. In the following the procedure is repeated for the remaining phases (Phase V and Phase W). Finally, resistance values of all three phase directions ( $r_{S,U}$ ,  $r_{S,V}$ ,  $r_{S,W}$ ) are estimated and available for further processing. Due to the fact that not only the resistance value but also the spatial position (phase direction) is identified through the direction of the applied voltage phasors, the resistance values can be treated as vectors. The angular position corresponds to the phase direction of the inverter output voltage and the magnitude to the estimated resistance value. As a result, a set of three vectors is obtained each pointing in one main phase direction (4). One of the main advantages of the vector representation is given by the fact that asymmetries in the machine properties can be easily identified.

$$\begin{aligned} \underline{r}_{S,U} &= r_{S,U} \cdot e^{j0} \\ \underline{r}_{S,V} &= r_{S,V} \cdot e^{j2\pi/3} \\ \underline{r}_{S,W} &= r_{S,W} \cdot e^{j4\pi/3} \end{aligned} \quad (4)$$

In the next step the set of phasors is combined by spatially adding them up. In Fig 2 this is indicated by the summation block ( $\sum \underline{r}_{S,i}$ ) subsequently to the resistance vector formation. As a result a single space vector is obtained. Caused by the angular directions of the three resistance phasors a zero sequence component is obtained in the case of a healthy machine. The healthy state result is thus a zero vector, independent of symmetrical resistance changes. Thus disturbing influences caused for example by temperature can be clearly reduced, or in case of equal temperature distribution within the machine even eliminated. Furthermore the above mentioned resistance portion of the other phase is also eliminated from the phase resistance.

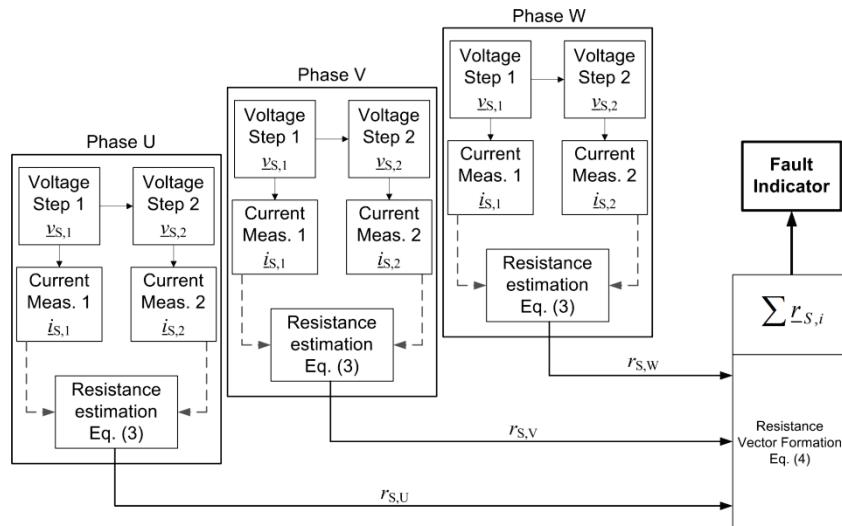


Fig 2: Block diagram of signal processing for fault indicator estimation

This final single vector will be denoted as ‘fault indicator’ in the following. Considering now an asymmetry induced by a fault (crack or deformation) in the conductors of one phase the fault indicator will point in the corresponding phase direction and its magnitude will represent the fault severity (asymmetry).

## Measurement and Experimental Results

### Current Reaction and Current Sampling

The measurement and signal processing procedure of the proposed method is simple to realize and can thus be implemented in an existing inverter control system. A voltage step is applied and the current reaction is measured. In inverter fed drive systems the voltage step is easily realized by applying a voltage phasor with pre-defined magnitude in a main phase direction. The current response is dominated by different parameters. In the first period the machine's transient inductance is the dominating factor. After the transient state settles, the current value will remain more or less constant and only be influenced by the stator resistance and voltage magnitude applied. Fig 2 shows the current response to a voltage step. The voltage phasor (magnitude 0.015 p.u.) was applied at 0 seconds in phase direction U. The diagram shows the trace of phase current  $i_{s,U}$ . For accurate fault indicator identification only current values within the constant state have to be sampled.

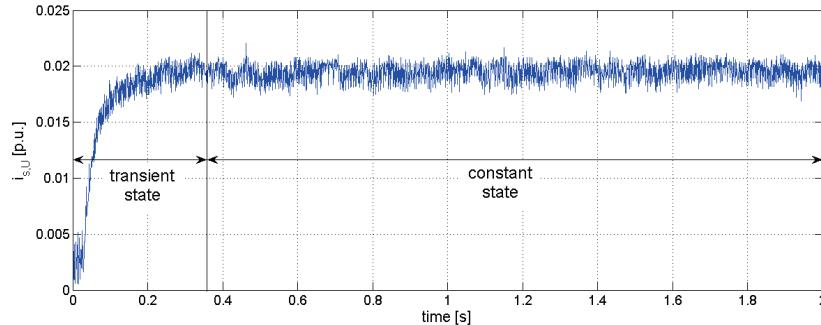


Fig 3: Phase current response on a voltage phasor step in phase direction U. Voltage step magnitude: 0.015 p.u.

**Table 1: Parameters of test machine**

| Parameter                   | value          |
|-----------------------------|----------------|
| Nominal Voltage             | 280 V          |
| Nominal frequency           | 75 Hz          |
| Nominal current             | 30 A           |
| Number of poles             | 4              |
| Number of Stator slots      | 36             |
| Stator resistance per phase | 0.145 $\Omega$ |

Basically it is sufficient to take only one sample value within the constant state period. However, on a real system the sensor signals are always noisy (as visible in the Fig 3).

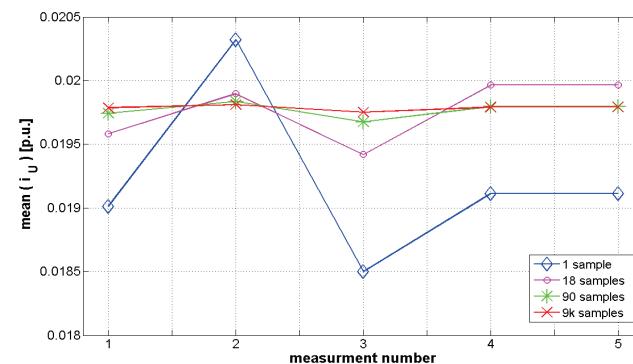


Fig 4: Impact of number of current samples during constant state.

To increase fault detection accuracy the noise must be eliminated. Here this is done by a mean value calculation from a set of current samples. In Fig 4 the impact of number of samples on measurement accuracy was investigated. A voltage step with a magnitude of 0.015 p.u. was applied 5 times to the

same phase (measurement number). The voltage step duration was set to 1.8 seconds (constant state) and the procedure was repeated 4 times each with a different number of current samples within the constant state. The number of samples was set as following for the corresponding measurement (Meas.): Meas. 1: 1 sample (blue, diamond), Meas. 2: 18 samples (violet, circle), Meas. 3: 90 samples (green, star), Meas. 4: 9k samples (red, cross). As expected the accuracy of the measured current value is strongly dependent on the number of samples. On the other side, a high sample rate also stresses the control and measurement system as all values must be processed. Implementing a low pass filter or moving average algorithms can reduce the current sample afford without the need of a large storage for the mean value calculation.

### **Simulation of winding conductor faults**

For proving the method's applicability and accuracy a test stand was set up with a standard machine. The machine was specially prepared to simulate faults in the stator winding conductor system. Simulation of such faults was realized by increasing the stator resistance of a single phase. A simple and effective way to simulate such an event is given by intentionally increasing one phase resistance by adding a resistor in line with the stator winding. The main advantages of this procedure are no stator winding destruction, fast realization, machine type independence and possibility to adjust the fault severity.

### **Experimental Setup and Results**

The test machine is an induction machine with 11 kW and the parameters presented in Table 1. The stator has full pitched windings and the rotor is a squirrel cage rotor with un-skewed rotor bars. The inverter is a standard voltage source inverter and the control and measurement unit is realized on a real time system programmable under MATLAB/Simulink. Verification of the methods accuracy has been done for several fault levels. Due to the small absolute resistance value of the stator winding (in the range of hundred mΩ) the additional resistor in series with the stator winding has to be in the same range. Therefore 4 copper wires with different lengths were chosen. The resistance values of all wires as well as the stator resistance of the machine were obtained by measurements as given in Table 2. The fault development can be approximated by an exponential behavior of the severity. In the first period the fault severity slope is quite low against time. Thus it is sufficient to activate monitoring sequences like the proposed method in a period of days or months. For example the proposed method can be executed just before the start up procedure of a drive system as the duration is within some seconds. The machine operating state was set to zero current and standstill when starting the measurement. The voltage magnitude of the first step was set to 0.01 p.u. and the second 0.03 p.u., respectively. Therewith it was ensured that the resulting current values are in a safety range wide below nominal value. Hence stator winding heating up is reduced and the current transducers are operated in their preferred range.

**Table 2: Identification of resistance values of additional resistors and test machine**

| Device under Test                 | Resistance [Ω] | Resistance [%] |
|-----------------------------------|----------------|----------------|
| IM stator resistance (Phase U)    | 0.145          | 100.00         |
| Stator resistance + Copper Wire 1 | 0.150          | 106.00         |
| Stator resistance + Copper Wire 2 | 0.158          | 109.50         |
| Stator resistance + Copper Wire 3 | 0.163          | 113.00         |
| Stator resistance + Copper Wire 4 | 0.176          | 121.50         |

### **Symmetrical machine**

In a first step the machine was investigated in the faultless, symmetrical stage. No additional wires were inserted to the machines terminals. Measurements were carried out as described in the previous section.

In Fig 5 the resistance values as well as the final calculated fault indicator are depicted in the complex frame which is related to the stator fixed frame ( $\alpha, \beta$ ). The blue crosses (x) show the

calculated resistance value depicted as complex values. The magnitude corresponds to the identified resistance value and the direction is defined by the spatial orientation of the applied voltage phasor. The green star finally represents the fault indicator as the spatial sum of the three resistance values. As can be clearly seen the fault indicator is located very close to the origin. Thus the symmetrical/healthy machine is identified.

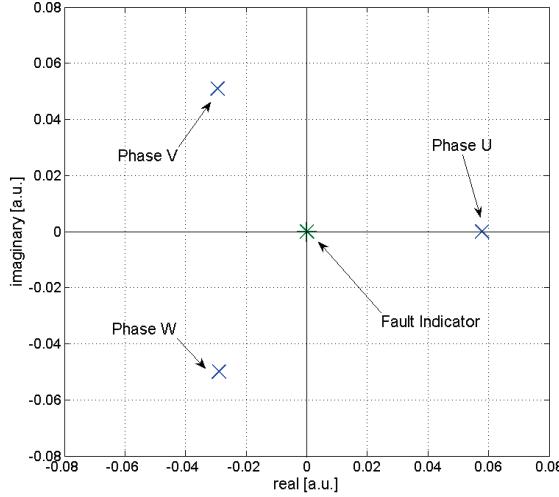


Fig 5: Phase values and Fault Indicator for symmetrical machine

### Simulation of incipient stator conductor fault

In the next step several different levels of developing stator conductor faults were realized to identify the method's accuracy. Therefore 4 different copper wires (described in Table 2) were connected in series with the machines terminals in all three phases.

The copper wire 4 was firstly connected to phase W and a measurement was carried out. After that the copper wire 3 was applied and a next measurement procedure was done. To prove not only the ability to detect faults but also to detect their location, copper wire 1 and 2 were connected to phase U. The wires in phase W were removed. In a last step copper wire 1 was finally connected to phase V and the measurement procedure repeated again. All the measurement results are given in Fig 6. Besides the fault indicator for the symmetrical machine (denoted 'Faultless'), all fault cases are depicted. Notation is given according to the resistance increase with respect to the phase resistance and the phase direction of the fault case. It has to be mentioned that the fault indicator for symmetrical machine also shows a slight offset. This results from several inherent asymmetries like material imperfection, connection resistances, sensor asymmetries etc. Thus a commissioning measurement was done to eliminate this offset. This measurement was repeated 5 times and the circle represents the maximum deviation. As the results show, each fault case can be clearly identified with its magnitude as well as the position.

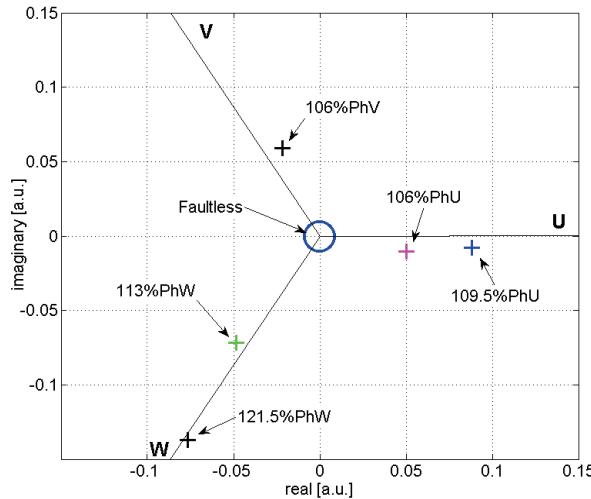


Fig 6: Fault indicator for healthy state and different fault cases.

## 2-Sensor based Current Measurement

In industry and propulsion applications the number of phase current sensors is often reduced to 2 (2-sensor). The main reasons are given by cost reduction and manufacturing space conditions. Using only two phase current sensor instead of three reduces also the number of subsequent hardware as wiring, amplifier, filter, analogue digital converter, e.g. But also backup safety systems can be taken into considerations for example if one phase current measurement unit has a failure. Thus calculation of the stator current  $i_S$  in the space frame representation is realized by only two measured current values. To increase the acceptance of the proposed method measurements were carried out by using only two current sensors of the inverter. As the proposed method is based on the estimation of the phase resistance by current measurement, reduction using only two instead of three sensors will also influence the method's accuracy. To identify the accuracy deviation of 2-sensor application from the 3-sensor application the current sensor in phase V was disconnected from the control and measurement system. Current value of phase V was reconstructed by using  $i_U + i_V + i_W = 0$ .

In a first step the impact of current reconstruction on the accuracy of the calculated stator current  $i_S$  was investigated. As the current sensor in phase V was disconnected the highest error is expected in this phases. In Fig 7 the magnitude of the stator current phasor is plotted twice against time. The blue trace represents the 3-sensor case while the red one the 2-sensor case with phase V current reconstruction. The voltage phasor step was applied in phase direction V.

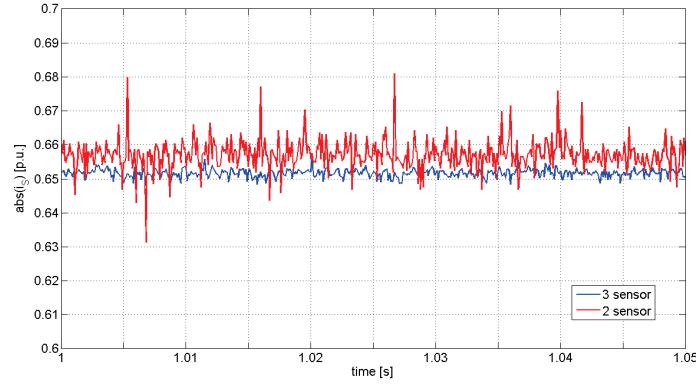


Fig 7: Stator current magnitudes for a voltage phasor step in phase V. blue: 3-sensor.  
red: 2-sensor (phase current V reconstructed).

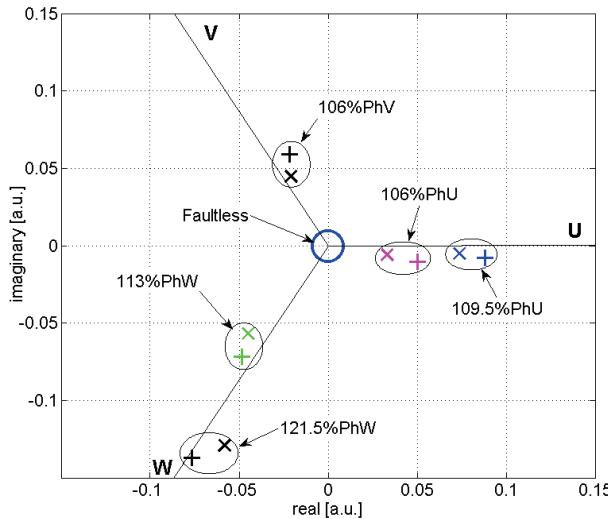


Fig 8: Fault indicator comparison for 3-sensor and 2-sensor case. Phase current sensor V disconnected.  
+: 3-sensor; X: 2-sensor.

Considering the mean value of both cases the deviation is very small. But on the other side the 2-sensor case is superposed by a higher noise. In the next step all the fault cases presented in Table 2 were repeated for the 2-sensor case. All the measurement results are presented in Fig 8 including the

results of Fig 6. The X represents the 2-sensor case measurements. Although one current sensor is missing a clear separation and identification of all fault cases is possible.

## Conclusion

The technique presented allows the detection of stator resistance changes and especially asymmetries in the winding system. Applying a short test voltage to the machines terminals and measuring the current reaction provides the base for the method. The voltage applied by an inverter is distorted due to several effects and cannot be directly used for stator resistance identification. A special test voltage pattern and signal processing chain reduces these impacts and provide a fault indicator. Faults can be detected with their severity and position. Developing open circuit faults were emulated by implementing additional resistance values in series with the stator, thus increasing the resistance in a single phase without disassembling and destructing the stator winding system. The results obtained have shown satisfying accuracy when detecting asymmetries in the stator resistance. It was shown that a resistance increase of 6% in single phase can be identified with its position and magnitude. Furthermore also measurements with only two current sensors (instead of three) were carried out to prove method's applicability in industrial drive systems. It was shown that the accuracy is only slightly affected.

## References

- [1] IEEE Committee Report; "Report of large motor reliability survey of industrial and commercial installation, Part I," *IEEE Transactions on Industry Applications*, vol.21, no.4, pp.853–864, (1985).
- [2] IEEE Committee Report; "Report of large motor reliability survey of industrial and commercial installation, Part II," *IEEE Transactions on Industry Applications*, vol.21, no.4, pp.865–872, (1985).
- [3] S. Nandi, H. A. Toliat, and X. Li, "Condition monitoring and fault diagnosis of electrical motors—A review," *IEEE Trans. Energy Convers.*, vol. 20, no. 4, pp. 719–729, Dec. 2005.
- [4] Tallam, R.M.; Sang Bin Lee; Stone, G.C.; Kliman, G.B.; Jiyoong Yoo; Habetler, T.G.; Harley, R.G.; , "A Survey of Methods for Detection of Stator-Related Faults in Induction Machines," *Industry Applications, IEEE Transactions on* , vol.43, no.4, pp.920-933, July-aug. 2007
- [5] Tallam, R.M.; Habetler, T.G.; Harley, R.G.; , "Stator winding turn-fault detection for closed-loop induction motor drives," *Industry Applications, IEEE Transactions on* , vol.39, no.3, pp. 720- 724, May-June 2003
- [6] D. A. Paice, "Motor thermal protection by continuous monitoring of winding resistance," *IEEE Trans. Ind. Electron. Instrum.*, vol. IECL-27, no. 3, pp. 137–141, Aug. 1980.
- [7] A. D. Inuwa, "Smart motor protection," Ph.D. dissertation, Univ. Sussex, Brighton, U.K., Aug. 1992.
- [8] L. A. S. Ribeiro, C. B. Jacobina, and A. M. N. Lima, "Linear parameter estimation for induction machines considering the operating conditions," *IEEE Trans. Power Electron.*, vol. 14, no. 1, pp. 62–73, Jan. 1999.
- [9] C. B. Jacobina, J. E. C. Filho, and A. M. N. Lima, "On-line estimation of the stator resistance of induction machines based on zero sequence model," *IEEE Trans. Power Electron.*, vol. 15, no. 2, pp. 346–353, Mar. 2000.
- [10] Stojcic, G.; Stankovic, J.; Joksimovic, G.; Vasak, M.; Peric, N.; Wolbank, T.M., "Increasing sensitivity of stator winding short circuit fault indicator in inverter fed induction machines," *Power Electronics and Motion Control Conference (EPE/PEMC), 2012 15th International* , vol. , no. , pp.DS2a.10-1,DS2a.10-6, 4-6 Sept. 2012
- [11] Stojcic, G.; Samonig, M.; Nussbaumer, P.; Joksimovic, G.; Vasak, M.; Peric, N.; Wolbank, T.M., "Monitoring of rotor bar faults in induction generators with full-size inverter," *Power Electronics and Applications (EPE 2011), Proceedings of the 2011-14th European Conference on* , vol. , no. , pp.1,8, Aug. 30 2011-Sept. 1 2011
- [12] Stojcic, G.; Nussbaumer, P.; Joksimovic, G.; Vasak, M.; Peric, N.; Wolbank, T.M., "Separating inherent asymmetries from high sensitivity rotor bar fault indicator," *Diagnostics for Electric Machines, Power Electronics & Drives (SDEMPED), 2011 IEEE International Symposium on* , vol. , no. , pp.9,15, 5-8 Sept. 2011
- [13] Jong-Woo Choi; Seung-Ki Sul; , "Inverter output voltage synthesis using novel dead-time compensation," *Power Electronics, IEEE Transactions on* , vol.11, no.2, pp.221-227, Mar 1996
- [14] Bolognani, S.; Zigliotto, M., "Self-commissioning compensation of inverter non-idealities for sensorless AC drives applications," *Power Electronics, Machines and Drives, 2002. International Conference on (Conf. Publ. No. 487)* , vol. , no. , pp.30,37, 4-7 June 2002
- [15] Bojoi, I. R.; Armando, E.; Pellegrino, G.; Rosu, S. G., "Self-commissioning of inverter nonlinear effects in AC drives," *Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International* , vol. , no. , pp.213,218, 9-12 Sept. 2012
- [16] Pellegrino, G.; Guglielmi, P.; Armando, E.; Bojoi, R.I., "Self-Commissioning Algorithm for Inverter Nonlinearity Compensation in Sensorless Induction Motor Drives," *Industry Applications, IEEE Transactions on* , vol.46, no.4, pp.1416,1424, July-Aug. 2010