Detecting High-Resistance Connection Asymmetries in Inverter Fed AC Drive Systems

G. Stojčić, T. M. Wolbank

***Abstract* – The wiring system between inverter and the machine consists of different parts connected by metal-to-metal joints. High load currents lead to an increase temperature of the connections and higher material degradation. Basically, these effects result in an increased resistance in one phase. If such faults are not identified timely an unexpected outage of the whole system can be a consequence. However, the degree of reliability of the wiring system should not be less than that of the machine or inverter. Detecting such small resistance incensement provide the possibility to react timely on the occurred fault. In this paper a method is presented to detect open-circuit faults in the stator windings of an inverter fed drive. The method gets along with the hardware already present and doesn't need additional sensors etc. By applying voltage phasor steps to the machine terminals and measuring the resulting current the phase resistance can be estimated. By combination of the current direction with the phase resistance value resistance phasors can introduced. With these phasors a high sensitive fault indicator is generated able to detect connection fault severity and position. Measurements on a laboratory test stand for different fault configurations prove the applicability and accuracy of the proposed method.**

***Index Terms*--fault detection, wiring system, high resistance connections, induction machine, inverter fed,**

I. Introduction

In industry applications and propulsion systems the electrical circuit between the inverter and the machine is composed of numerous conductors, terminal blocks, switches, fuses, circuit breakers etc. All these parts are connected through joints which are usually metal-to-metal connections and introduce a source of additional resistance in the electrical circuit.

Considering a metal-to-metal connection at a joint it is well known that real surfaces are not flat but perforated. Thus, only small regions of the connecting surface are connected. Basically, metals which are usually used in electrical circuits like aluminum, copper and brass are surrounded by a non-conductive oxide film. Only in areas where this oxide film is fractured by the contact pressure a real metal-to-metal connections is established and thus, this cluster of micro-spots is the conducting part [1]-[2].

Exposing the connection to high currents as this is common in industry and propulsion applications leads to a temperature increase at the metal-to-metal areas above the material bulk temperature. This temperature increase has an influence on the degradation process and thus oxide film growth. Especially overload or short circuit currents lead to an intensive over-temperature and high degradation and resistance increase.

Another effect influencing the connection resistance is given by load cycling. This effect has no influence on the degradation process but on the mechanical pressure and force of the connecting parts like bolts and clamps. Here the thermal expansion of different materials is the leading cause. Considering a connection joint where one material has an expansion coefficient twice of the other one the pressure after heating up the connection will also double. This leads to a deformation of the geometrical properties of the connecting parts and finally to cracks [2].

Finally also the ambient effects in rough areas like moisture, dust, debris, ambient temperature changes, vibrations and external mechanical forces, etc. lead to
A higher wear and corrosion of the regarding parts.

All these effects together, result in an increased resistance of a connection and thus, in reduced efficiency of the connecting parts and the whole system. However, the degree of reliability of the electrical circuit should not be less than that of the inverter and machine. Investigations have shown that high resistance connections are among the main causes for failures in electrical systems [5],[6],[7]. Furthermore not only the high resistance itself is the main problem but also the following propagation. For example a resistance increase in one phase leads to voltage asymmetry in the stator winding and finally to stator winding defects which are among the most frequent failures [3]-[10].

In the past years numerous investigations have been done and methods developed to detect high resistance connections [8]-[14]. All the methods show good accuracy when detecting high resistance connections. However, most of the methods have been developed for line fed machines and can thus be hardly applied to inverter fed drives. Another drawback is given by the usage of additional sensor as e.g. voltage sensors which are usually not applied to inverter fed drives and raise the system costs. Furthermore most of the investigations have focused on already occurred faults in the electrical circuit.

Therefore reliable condition monitoring methods must be developed applicable to inverter fed drives. The common visual inspections and manual resistance measurements are reliable but not always applicable. Considering the drive in a traction system, the connections and joints are usually not easy accessible. Thus, such methods are associated with the disassembling of the system and thus not usable for continuous monitoring.

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The fault developing mechanism in the starting phase develops in a special manner. Considering the joint connection temperature equal to the ambient temperature at the beginning, the resistance increase will not be significant and negligible and thus also hardly detectable by conventional methods. By increasing the current through the connections due to demanded machine load the resistance will also rise. Assuming now a faulty connection, the resistance slope in one phase will be higher than in the remaining phases. Such fault cases will be denoted as hot contact point (HCP) in the following, due to the temperature dependent behavior and will be the point of main effort in this paper. Detecting HCP faults provides the possibility to react timely and to reduce the impact of subsequent fault.

In this article a method is presented to detect HCP faults. The method is based on the measurement of resulting current reaction to voltage phasor steps generated by the inverter. A benefit of the proposed method is given by the fact that only the inverter built-in standard current sensors and no additional hardware is needed. Measurements on a test stand with a voltage source inverter, an 11kW induction machine and a special designed terminal board will prove the method's applicability as well as the accuracy. However, for the sake of completeness, it must be mentioned that the presented method is only applicable while machine is at standstill and not running.

II. Identification of Phase Resistance

Identification of the resistance value of a system is usually achieved by applying a voltage or current to the systems terminals and measuring the resulting current or voltage. The resistance value can then be easily obtained by Ohm's Law. This procedure is usually applied to ohmic' materials like resistors and wires as present in an electrical drive system.

Considering a drive system consisting of an inverter, wiring, connectors and the electrical machine, the mentioned procedure can be realized by applying a voltage phasor by the inverter to the machine terminals and measuring the current by the inverter built-in current sensors. Now, due to the knowledge of both values the resistance value of the system can be easily calculated. But it must be mentioned that the voltage applied to the machines terminals is disturbed by inverter non-idealities and usually very difficult to be accurately identified without additional inverter output voltage sensors. Such voltage sensor are related with higher costs and are not necessary for the control and thus not applied to common drive systems.

The inverter output voltage is generated by switching of the inverter, known as pulse width modulation (PWM). Additionally to the discrete pulses, there are also other phenomena present arising from the switching devices inherent characteristics, namely: voltage drop, output voltage transitions slope, turn off/on time and the inverter dead time. All this phenomena influence the resistance estimation through the distortion of the inverter output voltage. These effects must be eliminated or reduced to achieve and accurate resistance estimation.

The inverter dead time carries the majority of all disturbing effects. Due to the fact that the inverter dead time is defined by hardware its influence can be clearly reduced by a special voltage pattern procedure given in the following.

Basically the method presented is based on two applied voltage phasor steps and measurement of the current response within these voltages (1). These measurements results are combined to eliminate the inverter dead time influence. The applied voltage phasors have the same direction but different magnitudes. The measurement is applied at standstill with zero flux and no load. As only the resistance value is identified and only steady state values are considered the resulting current response has also the same direction.

$$\begin{aligned} v_{S,1} &\rightarrow i_{S,1} \\ v_{S,2} &\rightarrow i_{S,2} \end{aligned} \tag{1}$$

The resistance can then be calculated by the differences from both obtained values as given in (2) and (3).

$$\begin{aligned} \Delta v &= v_{S,2} - v_{S,1} \\ \Delta i &= i_{S,2} - i_{S,1} \end{aligned} \tag{2}$$

$$r = \frac{\Delta v}{\Delta i} = \frac{v_{S,2} - v_{S,1}}{i_{S,2} - i_{S,1}} \tag{3}$$

This obtained resistor value now represents the phase resistance in the corresponding phase direction. The procedure is repeated for each phase direction so all phases are identified and compared and combined to one resulting value. Thus symmetrical influences (stator resistance) can be clearly reduced and a representation of the phase asymmetry is obtained.

III. Signal Processing and Fault Indicator

As shown above a special voltage pattern provide the possibility of phase resistance estimation for inverter-fed machines. A high-resistance connection at a joint leads to an increased resistance value in the corresponding phase and therefore a specific signal processing and fault indicator is developed to identify such asymmetries.

In a first step a voltage phasor is applied in one of the main phase directions (Phase U). Meanwhile the reacting current is measured. After that a second voltage phasor is applied to the same phase direction but with a different magnitude and the current is sampled again. All the parameters are forwarded to a resistance estimation block realized by (3). The voltage signal applied to phase U is shown in Fig. 1. The procedure is repeated subsequently

to the remaining phases. Finally, resistance values of all three phases are obtained (r_U, r_V, r_W). In the following this values are denoted as 'resistance phasors'. Basically these phasors are only representative of the phase resistance values and are not comparable with other phasor values like voltage, current or flux in the space vector frame.

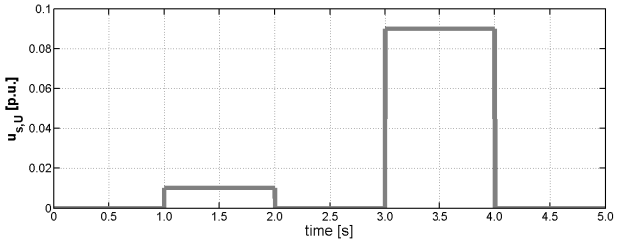

Fig. 1: Applied voltage signal to phase U.

Now, as the resistance values can be allocated to the phase direction the resistance is transformed from a scalar to a vector with the estimated value as magnitude and corresponding phase direction as angular position (4).

$$\begin{aligned} \underline{r}_U &= r_U \cdot e^{j0} \\ \underline{r}_V &= r_V \cdot e^{j2\pi/3} \\ \underline{r}_W &= r_W \cdot e^{j4\pi/3} \end{aligned} \tag{4}$$

In the following step, the set of resistance phasors is combined by adding them up spatially. As a result a single space vector is obtained. In the healthy/symmetrical machine state all phase values have the same magnitude leading to a zero sequence component that is eliminated by the vector calculation. The healthy state result is thus a zero vector, independent of symmetrical resistance changes caused for example by temperature in the stator winding.

Assuming a high-resistance connection in a phase the single vector will point in this phase direction and the magnitude will correspond to the fault severity. Thus, this calculated single vector will be denoted fault indicator in the following. For a clearer presentation the described procedure is given as a block diagram in Fig. 2.

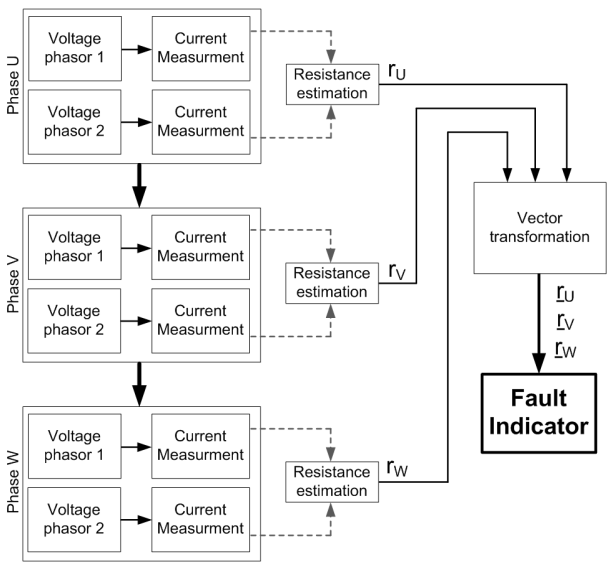

Fig. 2: Block diagram of proposed method

IV. Experimental Setup and Measurement Results

A. Experimental Setup

To verify the applicability of the proposed method a laboratory test stand was installed with a 280V 11kW squirrel cage rotor induction machine with the parameters given in Table I and a voltage source inverter. The control and measurement system is realized on a computer system programmable under MATLAB/Simulink. Additionally a special terminal board was designed to realize a simple and non-destructive simulation of high-resistance connections in the inverter-to-machine wiring system. By changing the conductor between the input and output side of the terminal board a distinct resistance change can be adjusted. This is preferably done by copper wire or a bridge made of tin. A temperature measurement unit enables the verification of temperature changes in the stator winding system and the connectors. The schematic diagram and the terminal board are presented in and , respectively.

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 Ω

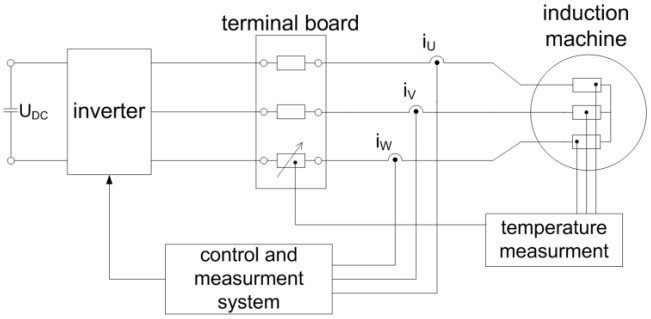

Fig. 3: Schematic diagram of the test stand

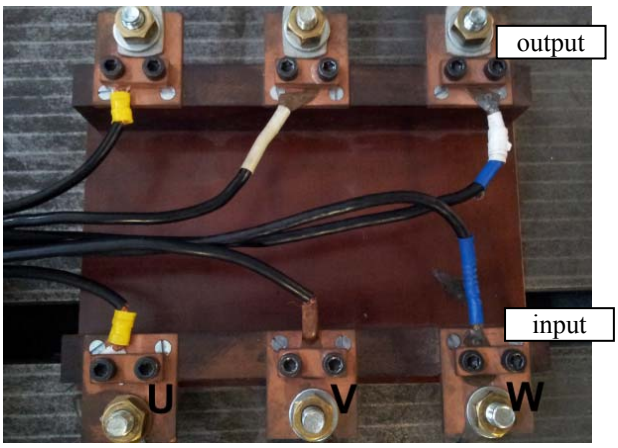

Fig. 4: Terminal board with for HCP fault emulation

As can be seen in the terminal board is realized by joint connections made of solid copper on the incoming and outgoing side. In the symmetrical case all three joints are connected by equal wires and/or couplers. By applying coupler of another material and/or dimension a distinct change in one phase can be realized without destruction of the setup. So, an easy and fast switching between faultless and faulty cases is realized for investigation of the proposed method.

B. Measurements to increased phase resistance

To prove the accuracy of the method several measurements and configurations were realized. In a first step a symmetrical configuration was investigated and all junctions were connected by copper wires. These copper conductors are emulating real connectors in a drive system. All the copper conductors have the same geometrical dimensions and thus equal resistance values. These measurements serve as reference and can be seen as an initial point of an excising system before a fault has occurred. As described in the previous section the method is based on the current reaction to a voltage phasor step. In Fig. 5 the fault indicator (green star) and the phase resistance values $\underline{r}_U$, $\underline{r}_V$ and $\underline{r}_W$ (blue crosses) for the healthy case are presented. The axis scaling is given in arbitrary units [a.u.] corresponding to the signal processor's internal representation and the complex plane is representing the stator fixed frame. As already mentioned, the combination of the resistance phasors to one single fault indicator phasor leads to a zero component in the healthy case as can be very well seen in the Figure. However, this measurement is realized by a low magnitude of the voltage phasor steps (first step: 0.005 p.u. and second step: 0.02 and the step duration was set to 5 seconds.

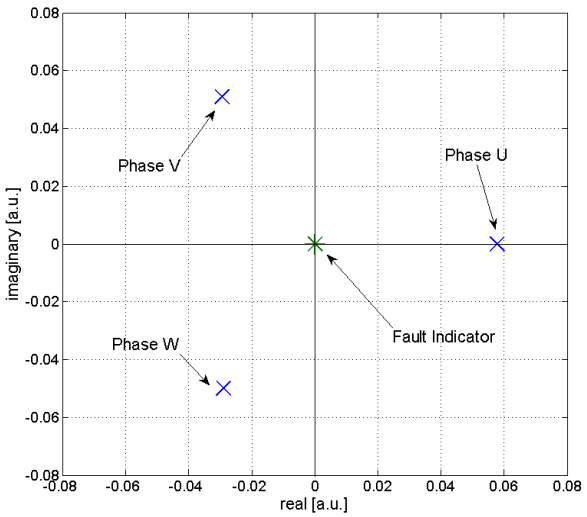

Fig. 5: Phase resistance values and fault indicator for healthy case in the complex plane.

In further consequence the copper conductor in phase W was exchanged with a longer conductor to prove the methods accuracy to already existing increased connection resistance. The resistance of healthy phase paths was measured to 10.8 mΩ while in the faulty path to 18.0 mΩ, what leads to an increase of 60%. The fault indicator in the complex plane for this case together with the indicator for the faultless case is presented in Fig. 6. The indicator has a clear deviation from the origin and the faultless case, respectively. Furthermore, due to the position of the fault indicator in phase direction W the faulty phase can be identified.

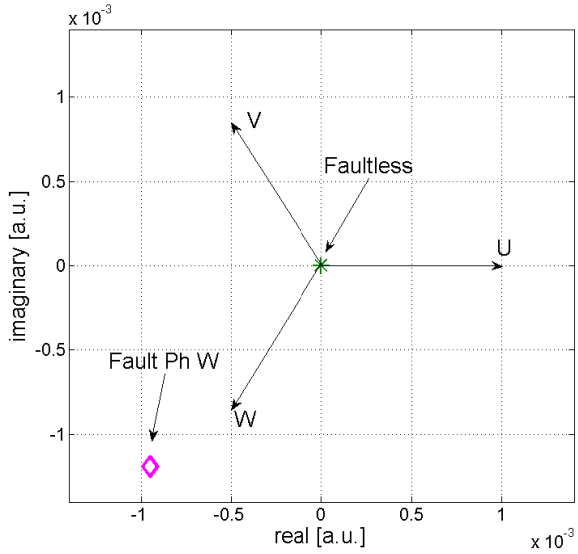

Fig. 6: Fault indicator in the complex plane for fault realized in Phase W by a resistance 60% higher than for healthy phases (U and V).

C. Measurements for HCP fault detection

As already mentioned, to keep the reliability at a high level it is necessary to detect faults in their early stage. Therefore, an experiment assembly was set up to emulate the behavior of a HCP in an early stage. To realize the temperature increase and thus the resistance increase of the faulty connection by current load, a bridge made of tin was applied to the terminal board in phase W as can be seen in Fig. 7. For identification of the resistance-to-temperature relation the temperature of the tin bridge is measured by a thermo couple. Due to the fault characteristics the resistance of all three connections is equal at ambient temperature. Thus, the tin bridge resistance at ambient temperature was set by the geometrical dimensions equal to the copper conductor resistance of 10.8mΩ.

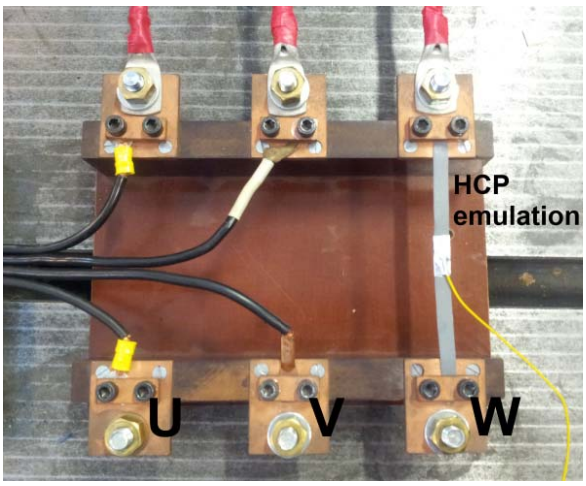

Fig. 7: Terminal board with HCP emulation in phase W by a tin bridge.

To get a clear impression of the experimental setup behavior during current load, a voltage phasor step with duration of 120 s was applied to the phase direction W. The pulse magnitude was set to 0.05 p.u. for both cases. The temperature of the HCP and copper conductor, the current response as well as the current difference are presented in Fig. 8 for the pulse duration. The temperature increase of the copper conductor can be neglected compared to the tin bridge, emulating the HCP. The current value in phase W for both cases starts at 0.857 as the resistance of tin bridge and copper conductor is equal at ambient temperature. At the end of the voltage pulse a clear difference of the current values can be seen due the increased resistance by current load induced temperature rise of the HCP. The current load has not only an impact on the HCP but also on the stator winding temperature. Thus, also the stator winding temperature was measured (as indicated in) in all three stator winding phases. However, due to the small increase of the stator winding temperature the impact of the stator winding resistance on the proposed method can be neglected. These temperature measurement results are given in Table II.

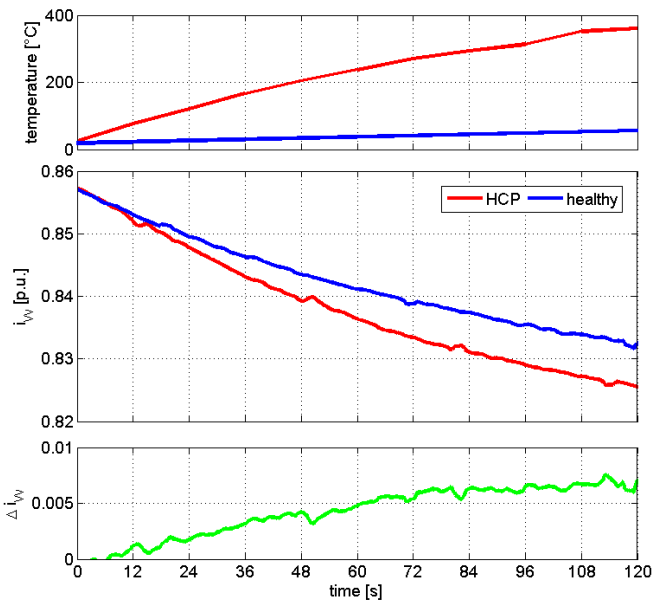

Fig. 8: Temperature, current [p.u.] and current difference progress of healthy and HCP case in Phase W due to a voltage phasor step in phase W (duration 120s).

TABLE II
STATOR WINDING TEMPERATURE DURING VOLTAGE PULSE IN PHASE W

Phase	U	V	W
start temp. [°C]	26	26	26
end temp. [°C]	33	33	38
environmental temp. [°C]	24		

In the next step the measurement procedure for fault indicator estimation, as presented in the previous section, was executed for the healthy case (all connections realized by copper conductor of equal length). The voltage phasor step duration was set to 30s each. The first voltage phasor was applied with a magnitude of 0.01 p.u. while the second with 0.05 p.u. The current measurement within the voltage phasor step duration was done with 5 kHz. To suppress the signal noise a running average calculation based on a digital filter was implemented in the control and measurement system. The used filter type is a direct form 2 FIR filter with a window length of 1000. The impact of the filtering process to the fault indicator is given in Fig. 9.

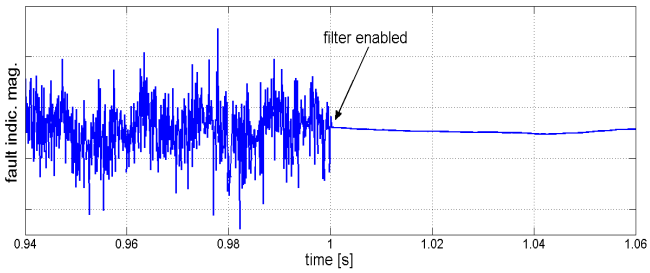

Fig. 9: Impact of a digital filter based running average calculation on the fault indicator signal (direct form 2 FIR filter with a window length of 1k).

Subsequently the copper conductor in phase W was exchanged by a tin bridge (HCP simulation) and the measurement procedure was repeated with the same settings as for the healthy case. The fault indicator signal of both cases is presented in . By the three dimensional frame a clear impression is given regarding the fault indicator trace within the voltage phasor step duration. The complex plane spans the base level as already shown in Fig. 5 and Fig. 6, respectively. The z-axis corresponds to the pulse duration (here 30 s).

The results prove that for the healthy case the fault indicator (blue trace) shows only negligible deviation from the origin and thus indicates a symmetrical configuration. On the other hand the fault indicator for a HCP configuration (red trace) shows a clear deviation from the origin with time. Furthermore, with the fault indicator direction the HCP can be assigned to a distinct phase, here phase W.

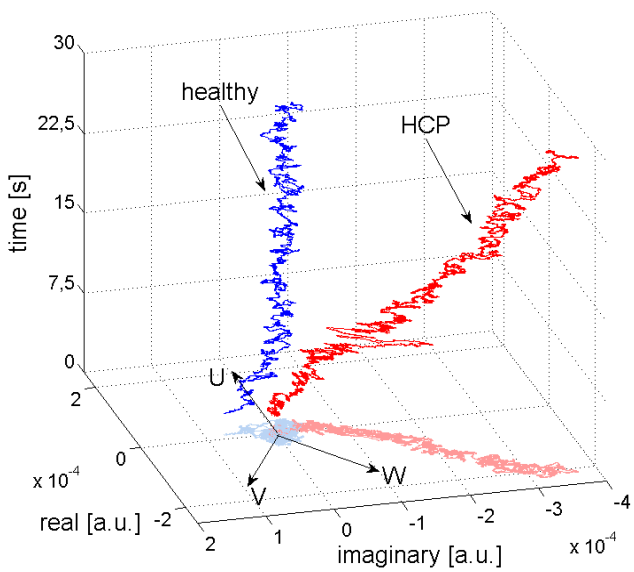

Fig. 10: 3D presentation of fault indicator vs. time.
Blue: healthy. Red: HCP.

Finally, to get an impression of the coherences between already occurred faults and the fault indicator a measurement for such a case was done. The connection of phase W on the terminal board was realized by a copper conductor with a resistance value of 52 mΩ. This is an increase of 481% with respect to the remaining phases. In Fig. 11 all the measurement results (healthy, HCP, occurred fault) are plotted together. As can be very well seen the fault indicator magnitude for the already occurred fault case (pink trace) remains almost constant versus time and can be clearly distinguished from the HCP case (red trace).

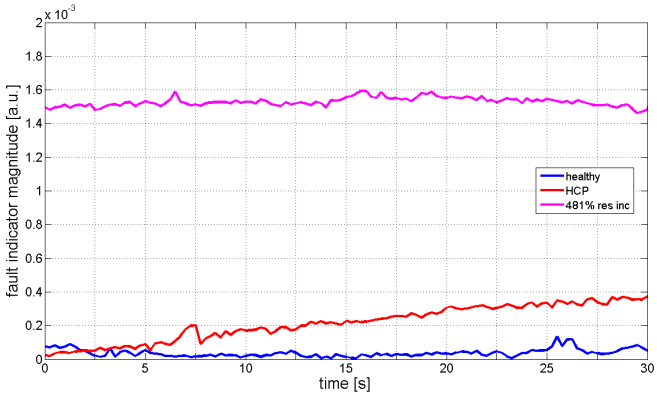

Fig. 11: Fault indicator magnitude vs. time for the healthy case and two faulty cases.

V. Conclusion

In the present paper a method was proposed and investigated to detect bad junction connections in the wiring system of inverter-fed drives. A big advantage of the method is given by the fact that not only already occurred faults but also incipient fault cases can be identified. The method is based on the identification of the phase resistance. The resistance estimation is realized by two voltage phasor steps and measurement of the current reaction. By transformation of the obtained phase resistance values to complex values and combining them to one phasor leads to a high sensitive fault indicator. By applying longer voltage phasor steps to the machine the time trace of the fault indicator can be used to identify not only already occurred connection faults but also incipient faults. A test stand was set up to prove the methods applicability. The test stand includes a special designed terminal board to realize non-destructive fault emulation. Measurements for different fault cases have proved the methods applicability and accuracy. It has been also shown that not only occurred but also incipient faults can be clearly identified by its magnitude and position with the proposed method.

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VII. Biographies

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