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THREE-PHASE CURRENT RECONSTRUCTION BY USING TWO CURRENT SENSORS

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Abstract- Current measurement has many application in power electronic especially in DC-DC converters and motor drives. In some application such as aerospace and aeronautic the volume and weight of the power electronic devices are very important issues. The present paper suggests a sensor arrangement for magnetoresistive current sensor which uses only two sensors without U-shaped conductors and reconstruction of the phase currents from the sensor signals. This arrangement reduces the size of power electronic devices.

Keywords: Current Measurement, Phase Current reconstruction, Magnetoresistive (MR) Current Sensor, Electrical Drives.

I. INTRODUCTION

Current measurement has many application in power electronic especially in motor drives. Modern electric three-phase drive systems are often controlled by inverters. For the efficient control of electric three-phase drive information about the phase currents is necessary [1]. Motor current is used as a control variable in drive systems. Recently developed drive control methods such Vector control and direct torque control require current measurement for control purposes [2]-[5]. The simple and low cost motor control methods such as speed sensorless and voltage sensorless approaches require current measurement to provide accurate control.

The vector control consists of controlling the components of the motor stator currents, represented by a vector, in a rotating reference frame d-q aligned with the rotor flux. The vector control system requires the dynamic model equations of the induction motor and returns the instantaneous currents and voltages in order to calculate and control the variables [2]. Often, the phase currents of the three phases are converted to corresponding currents in a two-axis coordinate system by means of the transformations (Clarke and Park Transformations) to allow a vector control of the electrical AC machines. In a conventional manner, all the phase currents are measured and used to control the torque and speed of a motor.

The phase currents in a drive system can be reconstructed by using only one current sensor placed in DC-link between the power supply and the inverter. This method however requires a complicated reconstruction algorithm [6].

The present paper proposes a simple arrangement for measuring the phase currents (three-phase) in an inverter. The measuring arrangement uses only two magnetic field sensors, and generates two signals, which are used for reconstructing three phase currents I_U, I_V and I_W from these two measurements. The measuring system does not require special conductor geometry, such as conventional U-shaped bus-bars for magnetoresistive sensors [7], thus is very compact and can be integrated cost-effectively in the inverter circuit, especially in aeronautic application to reduce the size of device. This leads to increased power density and reliability of the inverter.

II. CURRENT MEASUREMENT METHODS

The simplest way to measure a current is to connect a small series resistor (shunt resistor) to the load and measure the voltage drop across it. This voltage signal is a representation of the current, which can be easily measured and sent to control circuitry. This method however causes a thermal loss in sense resistor. Another drawback is the galvanic connection between the high voltage load or inverter and the low voltage circuitry. An isolation amplifier is needed between the sense resistor and the controller.

The second current measurement method is to use the Hall-effect sensors. In this method the magnetic field surrounding a current-carrying conductor is sensed. The sensor output is hence proportional to the current to be measured [8], [9]. An enhanced Hall-Effect based current sensor is the closed loop one, in which with an additional compensating winding the linearity and bandwidth is improved. A similar closed loop sensor, in which the magnetic field is sensed with a magnetic probe [10] or sensors based on storable inductor [9] has the same features like Hall-effect sensors.

Figure 1 shows such sensors as PCB-Mounting types. Such closed loop Hall-effect current sensor is balky and in some applications such as aeronautics leads to more weight and volume.

Magnetoresistive (MR) current sensors are another type of current sensors, which use the magnetoresistive properties of ferromagnetic materials to sense the magnetic field surrounding a current-carrying conductor. Magnetoresistance is the property of a material to change the value of its electrical resistance when an external magnetic field is applied to it [11].

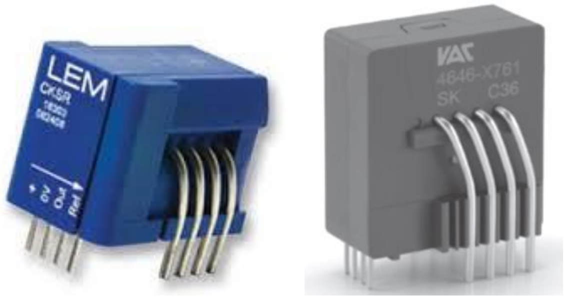

Figure 1. Left: Hall-effect current sensor (source: LEM);
Right: Current sensor with magnetic probe (source: Vacuumschmelze)

Four MR-elements are connected as a Wheatstone bridge on a substrate placed over a U-shaped current carrying conductor, which are usually embedded in PCB. To enhance the linearity of the current sensor a closed loop configuration according to Figure 2 is used [12].

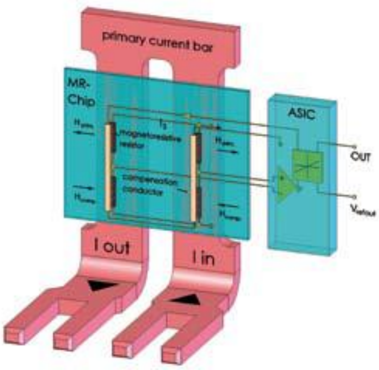

Figure 2. Closed loop magnetoresistive current sensor placed on a U-shaped current carrying conductor (Source: Sensitec)

Beside the galvanic isolation between current carrying conductor and signal processing circuitry, the small size of the sensor is an advantage in applications, in which the volume and size is an important factor.

III. PRACTICAL REALIZATION OF MR CURRENT SENSORS

The MR current sensors are mounted on a U-shaped current carrying conductors, which are usually embedded in PCBs. Further, clearances are to be maintain between the conductor arrangements to avoid the unwanted coupling of magnetic fields from other conductors. These U-shapes conductors lead to increase the area of the PCB, especially in three-phase current measurements, which is a disadvantage in some application such as aerospace and aeronautics (Figure 3).

Figure 3. Current carrying conductors proposed by MR sensor manufacturer (Source: Sensitec)

The MR sensing elements are connected as a Wheatstone measuring bridge, according to Figure 4 in a differential configuration. In this case the output voltage of the measuring bridge is proportional to the difference of the two currents affecting on the sensor.

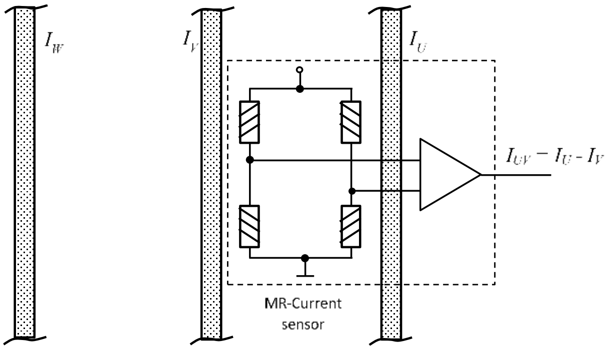

Figure 4. Differential arrangement of the sensing elements in Wheatstone bridge

This paper introduces a sensor arrangement, which requires no particular arrangement of bus-bars or printed circuit assemblies. This measuring arrangement leads to a saving of space on the PCB and weight as well. The proposed arrangement allows under certain circumstances to dispense with a third current sensor and to achieve the same reliability in terms of safety considerations.

In the proposed arrangement (Figure 4) the three conductors *U*, *V*, *W*, carrying the phase currents, as well as the current sensors 1 and 2 are arranged so that the sensor 1 is mounted symmetrical to the conductors *U* and *W* and the sensor 2 is mounted symmetrical to the conductors *V* and *W*. Thus, the sensor 1 is magnetically coupled to the conductors *U* and *V* equally, and the sensor 2 is magnetically to the conductors *V* and *W* equally too (It is assumed that the sensor 1 is decoupled from the conductor *W* and the Sensor 2 is decoupled from the conductor *U*).

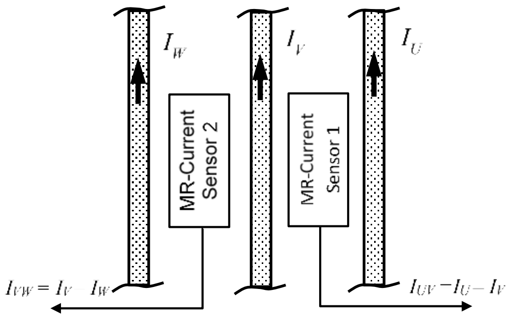

Figure 5. Two MR sensors are arranged to measure the phase currents

The resulting magnetic field affecting the MR current sensors 1 and 2 are respectively proportional to

$$\overrightarrow{I_{UV}} = \overrightarrow{I_U} - \overrightarrow{I_V} \quad (1)$$

$$\overrightarrow{I_{VW}} = \overrightarrow{I_V} - \overrightarrow{I_W} \quad (2)$$

These equation can be rewrite as a matrix equation

$$\begin{bmatrix} I_{UV} \\ I_{VW} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} I_U \\ I_V \\ I_W \end{bmatrix} \quad (3)$$

It is assumed, that the phase currents are symmetric. Thus the phase currents I_U, I_V and I_W can be reconstructed from these two measurements according to the vector diagram of Figure 6. The resulting equations are

$$\overrightarrow{I_U} = \frac{2}{3}\overrightarrow{I_{UV}} + \frac{1}{3}\overrightarrow{I_{VW}} \quad (4)$$

$$\overrightarrow{I_V} = \frac{-1}{3}\overrightarrow{I_{UV}} + \frac{1}{3}\overrightarrow{I_{VW}} \quad (5)$$

$$\overrightarrow{I_W} = \frac{-1}{3}\overrightarrow{I_{UV}} + \frac{-2}{3}\overrightarrow{I_{VW}} \quad (6)$$

and as a matrix equation

$$\begin{bmatrix} I_U \\ I_V \\ I_W \end{bmatrix} = \begin{bmatrix} 2/3 & 1/3 \\ -1/3 & 1/3 \\ -1/3 & -2/3 \end{bmatrix} \begin{bmatrix} I_{UV} \\ I_{VW} \end{bmatrix}$$

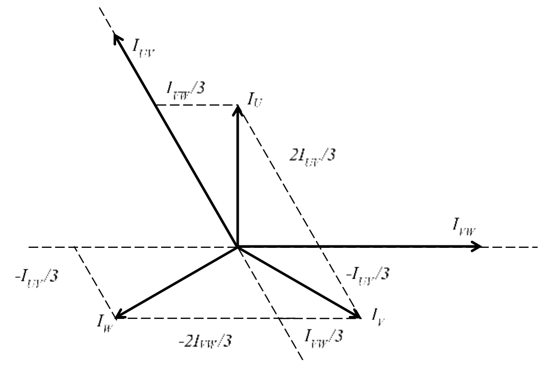

Figure 6. Vector diagram of phase current and the measured signals

The measured resulting currents I_{UV} and I_{VW} have a magnitude √3 times of the phase currents and are 120° phase shifted to each other. These equations are valid in the case of asymmetric phase currents as well.

The total measuring arrangement and the signal processing is depicted in Figure 7. The placements of the MR current sensors on the PCB can be optimized regarding the size of the PCB and the decoupling of the sensors from the irrelevant phases.

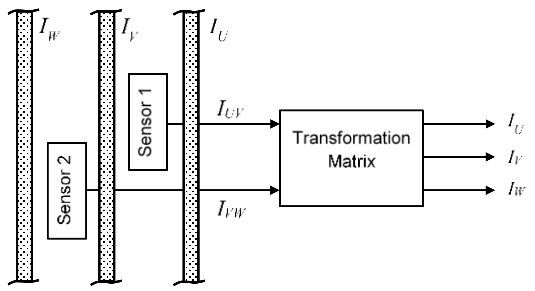

Figure 7. Placement of the sensor over the phase conductors and a simple µP for signal processing

IV. MEASUREMENT RESULTS

The measurements are carried out with a symmetric three-phase resistive load connected to a three-phase symmetric power supply and two MR current sensors CFS1000 from Sensitec GmbH. The current measurement are realized according to the Figure 7. The measured signal are acquired and processed to calculate the phase currents according to Equations (4)-(6). The power supply is adjusted to deliver phase currents 10 A_{peak}. The sensor output signals are shown in Figure 8.

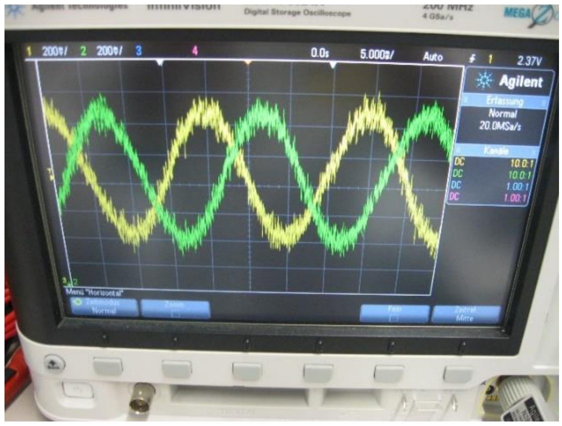

Figure 8. Measured output signals of the MR sensors

The sensor output is a current signal which flows in a resistor and generates a voltage signal proportional to resulting magnetic field. The output signal of both current sensors considering the calibration data correspond to a current amplitude 17.3 A_{peak} and the phase difference between these two signals is 120° which correspond with the vector diagram in Figure 6 regarding the amplitude and phase.

The results of reconstruction of the phase currents are depicted in Figure 9. As seen the reconstructed phase currents build a symmetric three phase system with an amplitude of 10 A_{peak}.

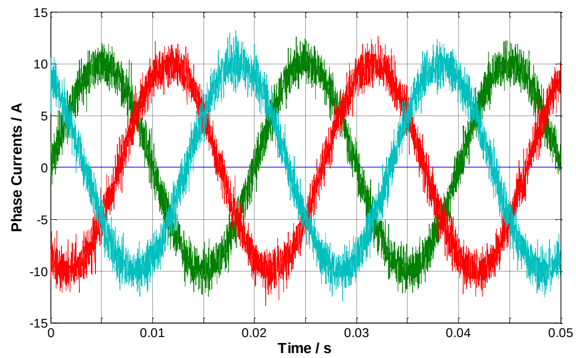

Figure 9. Results of reconstruction of the phase currents

V. CONCLUSIONS

A current measurement arrangement for a three-phase system by using two magnetoresistive current sensors was introduced. The three phase currents can be reconstructed from two sensor outputs. The reconstructed phase currents correspond with the vector diagram. This arrangement doesn't need U-shaped conductors in PCB, consequently simplifies the PCB layout and reduces the size and weight of the inverter. These features are very important in aerospace and aeronautic applications.

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BIOGRAPHY

Nejat Mahdavi Tabatabaei was born in Tehran, Iran, 1964. He received his B.Sc. degree in Electrical Power Engineering from University of Tabriz, Tabriz, Iran, M.Sc. (Dipl.-Ing.) and Ph.D. (Dr.-Ing.) degrees in Control and Instrumentation from University of Kassel, Kassel, Germany. In 1998-2002, he joined to University of Tabriz as lecturer and 2002-2007 was as scientific staff at University of Kassel. Since 2007 he is a senior research engineer in Liebherr-Elektronik, Germany. Since 2010 he is a lecturer at Baden-Wuerttemberg Cooperative State University (DHBW) in Friedrichshafen, Germany. Since 2013 he is an Assistant Professor at Seraj higher Education Institute, Tabriz, Iran. His research areas are control engineering, sensors, hybrid vehicles and energy storage systems.