

Real Time Rotor Bar Current Measurements Using a Rogowski Coil Transmitted Using Wireless Technology

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ABSTRACT

Rotor bar current measurement is a valuable step in verifying the theory of electrical machines design and control. However, because the rotor is moving, the approach is difficult to implement. This paper presents the design and evaluation of an approach to real-time rotor bar current measurement using the Rogowski coil as a current transducer. Rogowski coils have become an increasingly popular method of measuring current within power electronics equipment due to their advantages of low insertion loss and reduced size compared to an equivalent current transformer. The design of the associated integrating amplifier is discussed in detail, including the advantage, tradeoffs and limitation of the approach. Bluetooth wireless technology is employed to transmit data between the moving rotor and the computer which logs the data. Experimental results from a system for measuring the rotor bar current in a Brushless Doubly Fed Machine (BDFM) are presented.

1. INTRODUCTION

In electrical machines it is very often desirable to measure rotor bar currents in real time for purposes of machine design and analysis. The study of the Brushless Doubly Fed Machine (BDFM) is a particular example. The BDFM shows promise as a replacement for induction generators with wound rotors in wind turbines, but there is a need to measure rotor bar currents to verify models for the machine. However, measuring rotor bar currents is difficult because the rotor is moving. Since the measurement apparatus must be installed on the rotor, the dimensions must be minimized. Moreover, it must be possible to read the transducer data from the machine when the machine is moving. There is also likely to be a high level of electromagnetic (EM) interference, especially if the machine is inverter-fed. Furthermore, mechanical considerations must be taken account in the installation of the apparatus since, even at modest rotor speeds (1000 rpm), the centripetal

acceleration is of the order of 1000 m/s^2 for a frame size $D180$ machine.

This paper presents the design and evaluation of a rotor bar current measurement setup which employs a Rogowski coil for bar current sensing. A block diagram of the measurement apparatus is shown in Figure-1.

While the Rogowski coil sensing technique has not been previously employed for such an application, it is advantageous in this application due to its high accuracy and bandwidth, low weight and cost, and low sensitivity to parameter variations [1,2].

The integrator is necessary since the coil provides a voltage proportional to the rate of change of measured current. The integrator output can be connected to an analog to digital converter (ADC).

Recently introduced Bluetooth wireless technology (BT) is used to send the ADC output data to a PC. BT is the radio technology that allows devices to communicate with one another within a range of ten meters. BT therefore enables the data to be transmitted from the moving rotor without the need for slip-rings or other mechanical connections. The link speed, communication range, and transmit power level for BT were chosen to support low-cost, power-efficient, single-chip implementation of the current technology [3].

The setup is intended for measuring rotor bar currents in a Brushless Doubly Fed Machine (BDFM). The measurement of rotor current is an important step in verifying the theory of this machine, which has been proposed for use as an asynchronous generator for wind turbines [4]. The measurement setup is designed to measure the rotor bar current with the range of 10A to 3000A peak-to-peak and over a frequency range of 1Hz to 100Hz.

2. ROGOWSKI COIL DESIGN

A Rogowski coil is a low-noise air-cored current transducer. Rogowski coils have become an increasingly popular method of measuring current within power electronics equipment due to their advantages of low insertion loss and reduced size as compared to an equivalent current transformer [5].

Most commonly, Rogowski coil designs are one of two typical kinds: those which are wound on a rigid toroidal core former, and those which are wound on a flexible belt-like, or sometimes a worm-like core former. Both kinds may be made to be openable which makes placing them on a current-carrying conductor convenient.

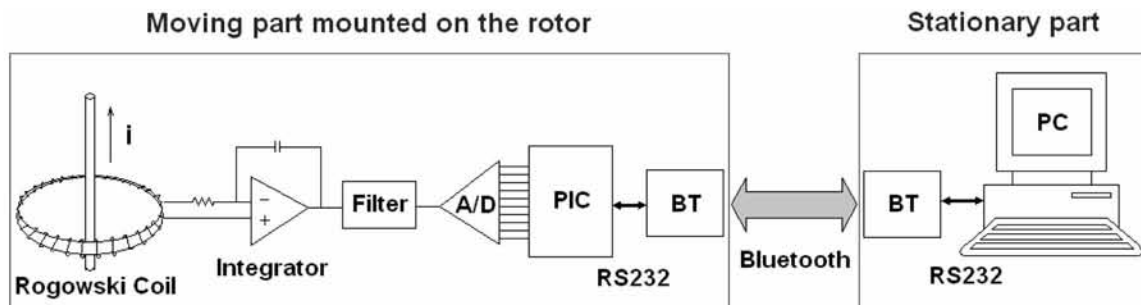


Figure-1: Block diagram of the measurement apparatus

In the application of rotor bar current measurement, the coil is wound on a flexible polyethylene former, such as is used for a coaxial cable, of sufficiently small cross sectional area to enable it to be threaded around a current carrying conductor and to have its ends clipped together. The end winding needs to be returned to its start along the central axis of the coil (i.e. in the middle of the former) to avoid sensitivity to magnetic fields parallel to the conductor which could be caused by other currents.

Although some researchers have investigated multi-layer coils to increase the sensitivity, single layer coils are more convenient from several viewpoints – ease of winding, better flexibility and relatively smaller inductance which gives a better bandwidth [6]. Figure-2 shows the Rogowski coil which is made for the rotor bar current measurement. The Rogowski coil has the design parameters and specifications shown in Table-1.

The output voltage $e(t)$ at the open terminals of the winding wound around the toroid is proportional to the time derivative of the current $i(t)$ flowing in a conductor passing through the toroid and is given by Equation-1.

$$e(t) = \frac{\mu_0 AN}{l} \frac{di}{dt} \quad (1)$$

which N is the number of turns, A is the cross section area, and l is the length of the toroid.

Table-1: Rogowski coil specifications

Coil parameter	Specification
Outside diameter (mm)	33.9
Inside diameter (mm)	25.7
Turns per meter (turn/m)	4090
Self inductance (mH)	9.18
Resistance (Ω)	2.68
Number of turns (turns)	380



Figure-2: Rogowski coil is used for rotor bar current measurement

3. INTEGRATOR DESIGN

The current can be determined by integrating the voltage at the terminals of the Rogowski coil. As any real op-amp used in an integrating circuit has an offset voltage, the output of the integrator will consist of the desired integral plus the integral of this offset voltage. The op-amp's offset is a constant quantity, and thus the integral of the offset voltage, which is added to the desired output of the op-amp, is a ramp that will always grow to be larger than the desired signal and will eventually saturate the op-amp.

In the application of rotor bar current measurement, as previously mentioned there is likely to be a high level of electromagnetic (EM) interference. Therefore noise rejection should be considered in order to filter all the interference produced by the machine and the inverter.

Due to the small voltages produced by the Rogowski coil (about $1 \mu\text{V}/\text{Hz}$ for 1 A flowing in a conductor), the design of a suitable integrating amplifier circuit is not a trivial matter. Furthermore, it is necessary that the power requirements of the circuit be kept to a minimum, as the device must be battery powered.

A simplified representation of the circuit used is shown in Figure-3. The AD8552, a dual operational amplifier, which has the correct combination of precision, low noise and low offset with a high gain bandwidth product and high slew rate, is used. Since the integrator gain increases as frequency decreases, thereby amplifying the low frequency random noise and zero frequency offset drift, it is necessary to reduce the integrator gain for frequencies below which measurement accuracy is not affected. A large resistor R_2 is put across C_1 to provide dc feedback for stable biasing. The effect is to roll off the integrator action at very low frequencies, $f < 1/R_2C_1$ [7]. The transfer function for the integrator shown in Figure-3 is given by Equation-2.

$$\frac{V_{int}(s)}{E(s)} = \frac{R_2}{R_1(R_2C_1s + 1)} \quad (2)$$

The Butterworth filter is used as an active filter which produces the flattest passband response, at the expense of steepness in the transition region from passband to stopband. It starts out nearly flat at zero frequency and bends over near the cut-off frequency f_c [7].

Figure-4 shows the pole-zero location of the integrating amplifier circuit. The integrating pole is placed at 0.02 Hz and the active filter poles are placed at 1 kHz . Frequency analysis of the circuit is shown in Figure-5.

A 50 Hz sinusoidal signal with two different noise signals super imposed is applied to the circuit and the output is shown in Figure-6.

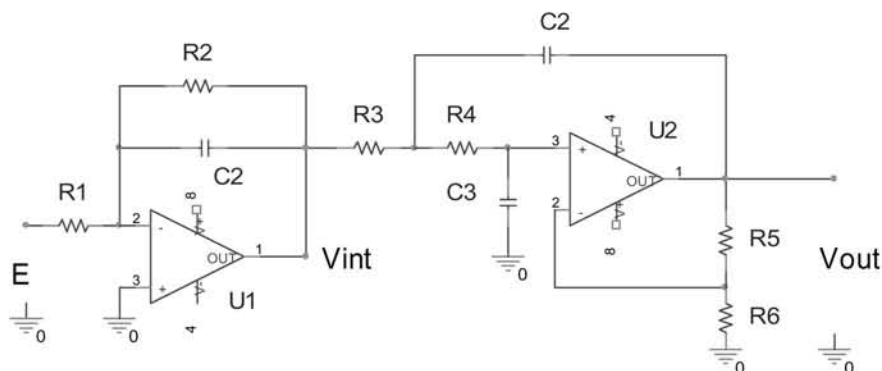


Figure-3: Integrating amplifier circuit

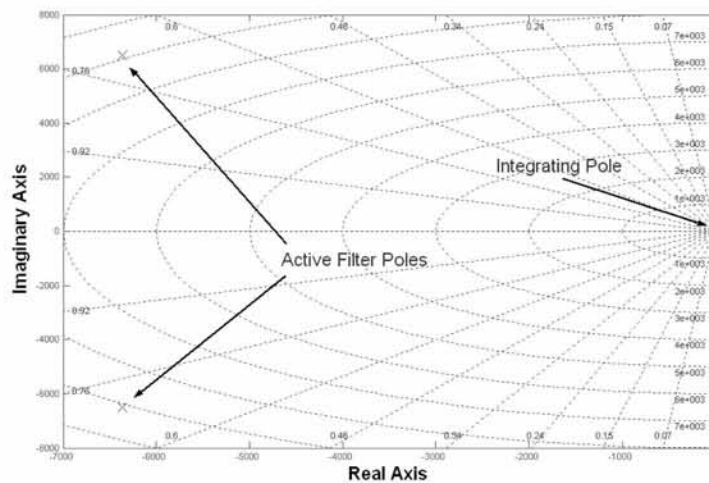


Figure-4: Pole-zero location of the integrating amplifier

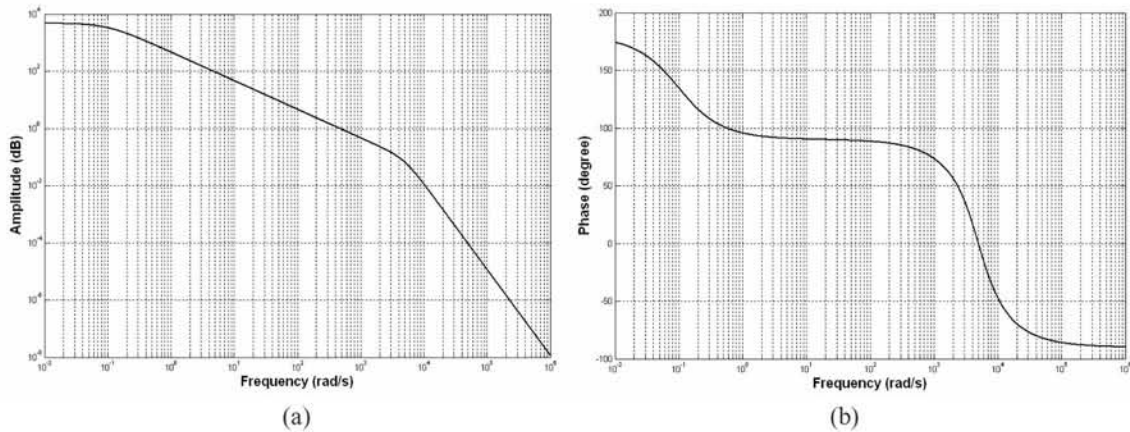


Figure-5: Frequency response of the integrating amplifier circuit (a) amplitude (b) phase

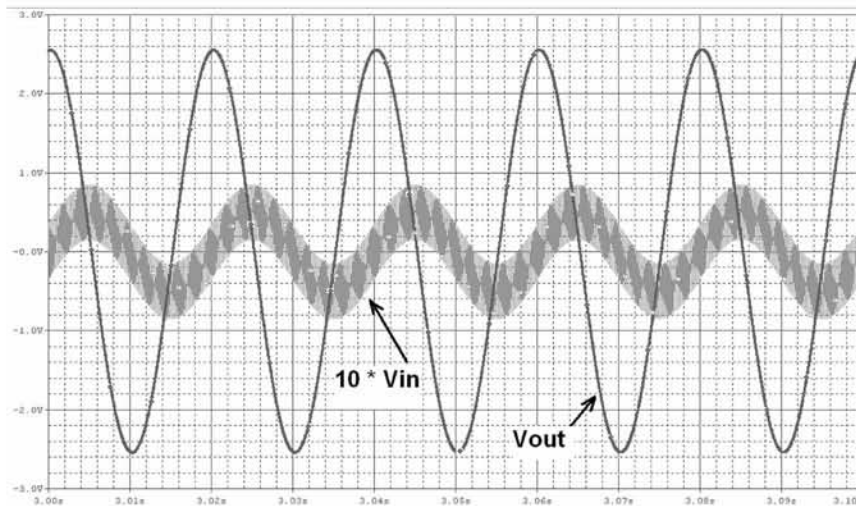


Figure-6: Real time simulation results

4. DIGITAL CIRCUITRY

The output of the integrating amplifier circuit is connected to a 10-bit analog to digital converter (ADC) which is contained with a microcontroller. The microcontroller is used to send the digital data over Bluetooth via a RS232 serial connection. Assuming a peak-to-peak rotor bar current of 3000 A, an accuracy of 3 A/bit is achieved. The baud rate of the data transmission is set to 115200 Bits/s which is limited by the COM port of the computer. This baud rate allows the 144 samples per cycle for a 50 Hz rotor bar current.

5. SERIAL CABLE REPLACEMENT USING BLUTTOOTH TECHNOLOGY

Bluetooth (BT) technology is used as a replacement for a serial cable for data communication between the machine and a computer. RS232 is chosen as a serial standard for the asynchronous communication. RS232 is a widely used standard for communications between industrial, medical and scientific apparatus. Despite growth in alternatives such as Ethernet and USB, RS232 remains the only communications standard which can offer the widespread interoperability and cost

effectiveness required by manufacturers of this equipment. However, the need for a physical, wired connection between devices can be inconvenient [8].

Bluetooth is a standard developed by a group of electronics manufacturers that allows any sort of electronic equipment to make its own connections, without wires, cables or any direct action from a user [9,10].

The challenge in rotor bar current measurement is to transmit the digitized data from the moving rotor to the computer. BT offers a solution to this problem. BT

was originally conceived as a replacement for the IRDA protocol for communication between laptops, PDAs, etc. However, Cambridge Silicon Radio (CSR) have produced software for their *BlueCore* single chip Bluetooth and DSP which implements an RS232 link over Bluetooth. Compared to other wireless technologies, BT is low cost and consumes very little power.

Two CSR's *BlueCore™* RS232 cable replacement modules are used for this application. The schematic of the serial communication profile is shown in Figure-7.

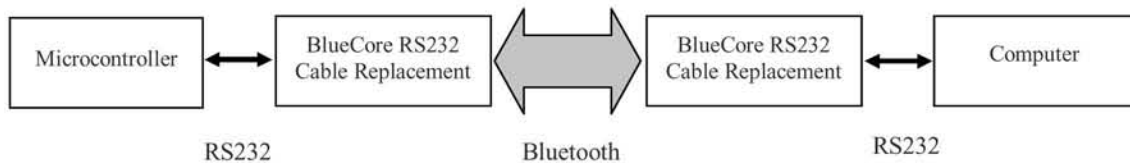


Figure-7: Serial communication profile

6. EXPERIMENTAL RESULTS

To establish the validity and degree of accuracy of the proposed design, the practical tests were conducted. Figure-8 shows the experimental rig which is used to measure a current going through a multi-turn wire to achieve a higher current level. The actual current (CH2) and the output of the integrating amplifier circuit (CH1) are compared in Figure-9. Figure-10 shows the current which is plotted with the data received by the computer.

As can be seen from the figures, very satisfactory performances have been obtained. The phase shift of 7 degrees produced by the integration amplifier circuit can be seen more clearly in figure-11.

measurement technique which employs a Rogowski coil current sensor. A coil and integrating amplifier design suited to the application is developed within the constraints of high accuracy and good noise rejection, low weight and cost and low power consumption. Bluetooth technology is used to transmit the data from the rotor to a computer's serial port.

The experimental results demonstrate the feasibility of the approach. It is concluded that the Rogowski coil with appropriate integrator design using the Bluetooth transmission medium offers a viable method of measuring rotor bar currents in moving machines. The approach can also be used when electrical isolation is required, as in high voltage machines.

7. CONCLUSIONS

The paper presents the design and evaluation of a real time rotor bar current

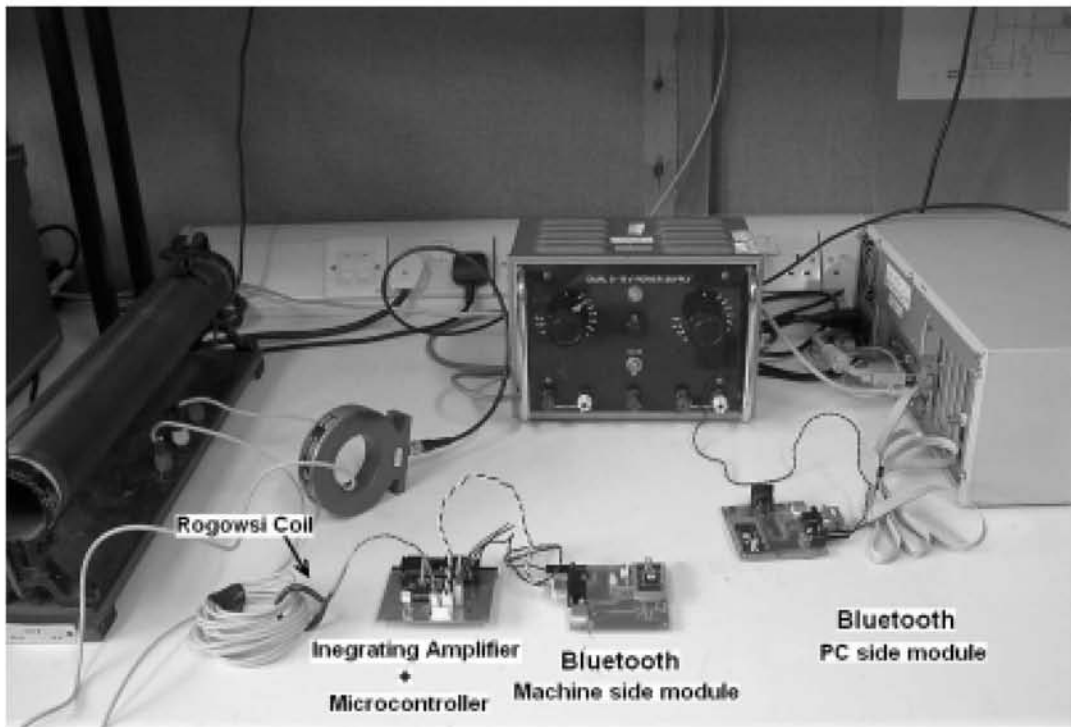


Figure-8: Experimental apparatus

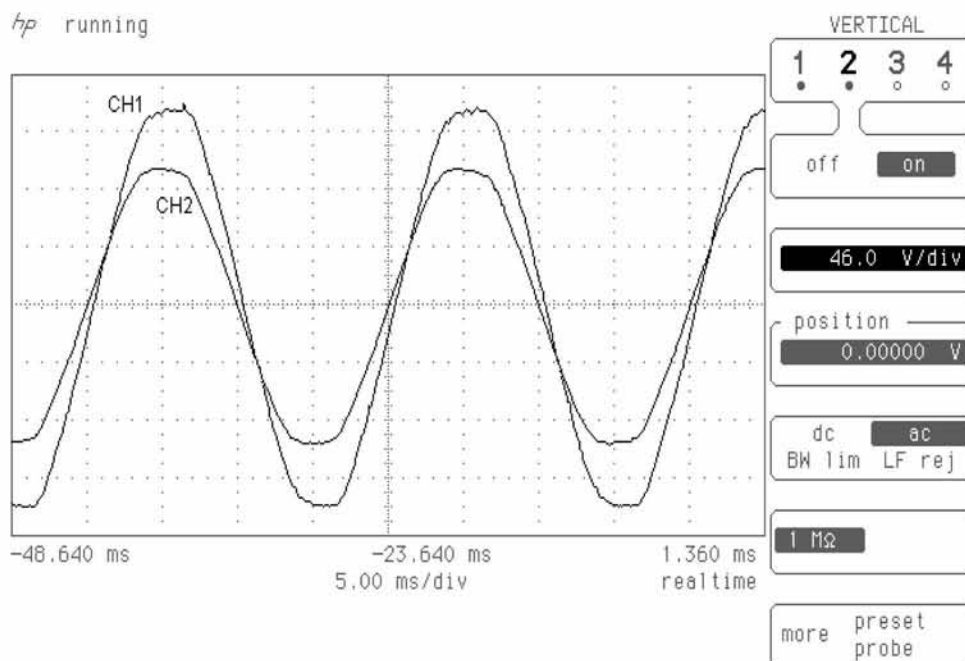


Figure-9: Actual and measured current comparison

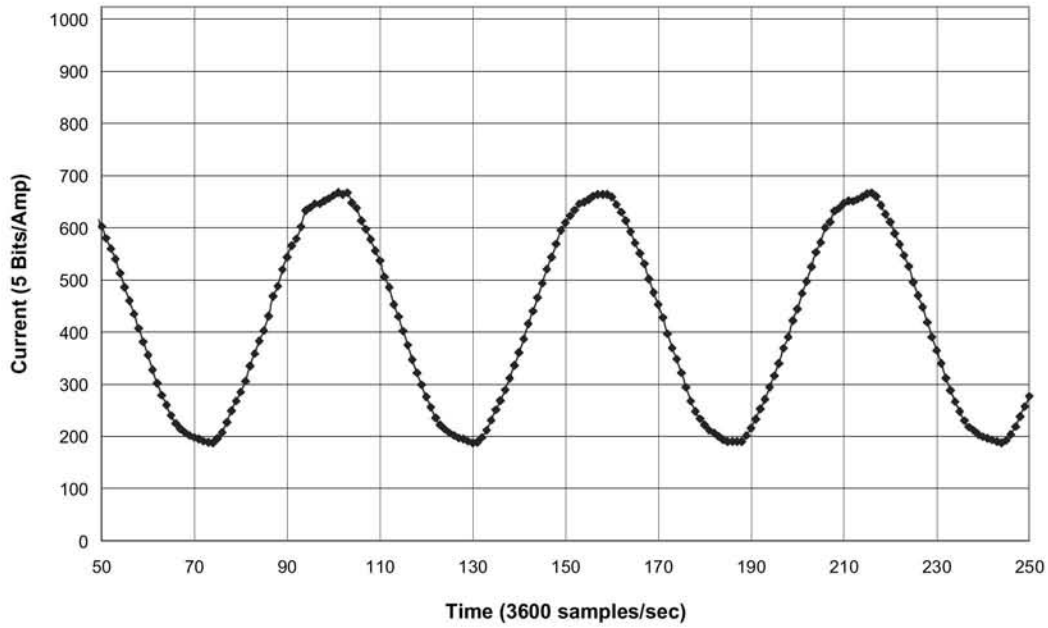


Figure-10: Current plotted with the data received by the computer

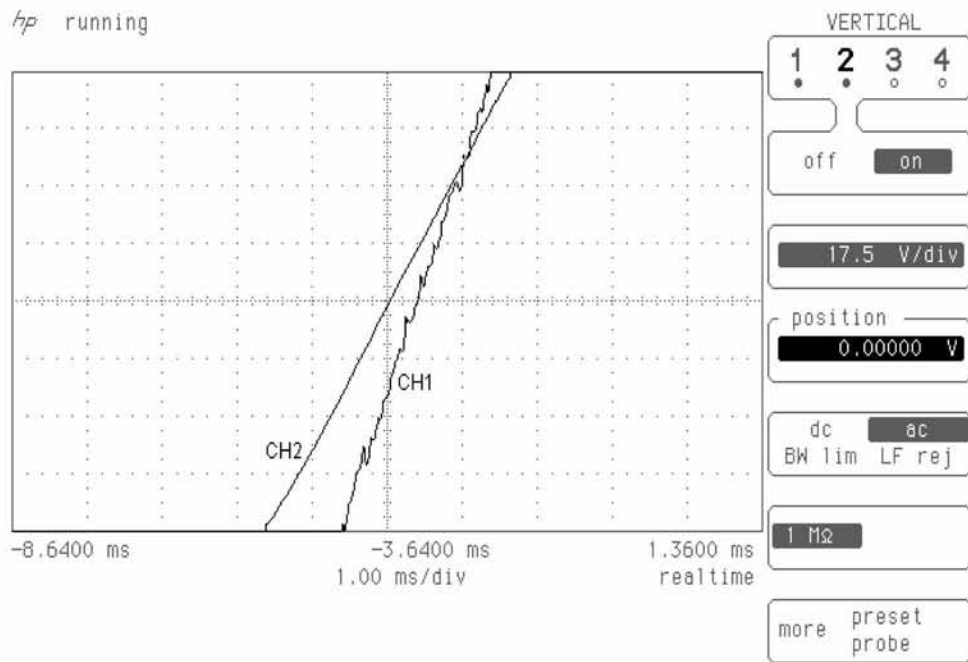


Figure-11: Phase shift between the actual current and the measured current

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REFERENCES

- [1] W. F. Ray, C. R. Hewson, "High Performance Rogowski Coil Current Transducers", Industry Applications Conference, Conference Record of the 2000 IEEE, vol. 5, pp. 3083 -3090, 2000.
- [2] C.D.M. Oates, A.J. Bumett, C. James, "The Design of High Performance Rogowski Coil", International Conference on Machines and Drives, IEEE2002, Conf. Publ. No. 487, pp. 568-573, 2002.
- [3] P. Bhagwat, "Bluetooth: Technology for Short-Range Wireless Applications", IEEE internet comp., vol. 35, no. 3, May/June 2001.
- [4] A. K. Wallace, S. Williamson, A. C. Ferreira, "Generalized Theory of the Brushless Doubly-Fed Machine. Part 1: Analysis", IEE Proceedings, Electrical Power Applications, 144(2):111-122, 1997.
- [5] z. Mingjuan, D. J. Perreault, V. Caliskan, "Design and Evaluation of an Active Ripple Filter with Rogowski Coil Current Sensing", Power Electronics Specialists Conference, PESC99, 30th Annual IEEE, vol. 2, pp. 874 -880, 1999.
- [6] J. D. Ramboz, "Machinable Rogowski Coil, Design and Calibration", IEEE Transactions on Instrumentation and Measurement, vol. 45, Issue: 2, pp. 511-515, April 1995.
- [7] P. Horowitz, W. Hill, "The Art of Electronics", 2ed edition, Cambridge University Press, 1989.
- [8] M.A. Mazidi, J.G. Mazidi, "The 80x86 IBM PC & Compatible Computers", Volume 2, Prentice Hall, Englewood Cliffs, 1995.
- [9] J. Kardach, "Bluetooth Architecture Overview", Mobile Computing Group, Intel Corporation, 2000.
- [10] M. Andersson, "Industrial Use of Bluetooth", ConnectBlue AB, Sweden, 2001.