Development of high DC-current measurement system using closed loop Hall Effect configuration

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Abstract. Recently, the requirement of high-power electric sources for the vehicle industry has been increased, this trend forces the research of DC power sources and storage to be developed faster. For supporting the development, the requirement of the robust measurement system cannot be avoided. In this paper, non-contact high DC-current measurement system had been developed using Hall effect sensing. By this principle, a wide range of current magnitude spanning from -169 A to 237 A with 0.25 A resolution by design was developed. The design of the instrument was extended from the conventional closed-loop configuration system. The magnetic field obtained from secondary current was used to “purify” offset voltage and by using absolute voltage subtractor, the offset voltage can be removed. By this approach, the error due to permanent magnetic fields of concentrator can be compensated. The sensor and the conditioning signal were coupled with the digital block and the measurement data can be observed from LCD and connected to the PC by interface software.

1. Introduction

Rapid developments of electric cars in order to build “green” low pollution transport mode has reached enthusiasm after the successful product launched by Tesla motor. The grown market proofed that reliable and efficient electric car on the grid is possible to be realized. The fact that it is even difficult to follow by other variants such as fuel cell powered vehicle [1]. As an example, Tesla Roadster can draw electric current around 40 A from allocated 100-200 A of the electric grid at a typical home in USA [2]. Besides the obviously known factor such as size and cost of the vehicle battery [3], [4], the efficient management of the electricity system is a critical factor for the electric vehicle. The system which deals with the high DC current should be supported by proper instrument and control system for measurement, monitoring and control of the electrical quantity such as voltage and current.

To deal with high magnitudes of DC current, the instrument system must be equipped with a robust, accurate, safe and reliable sensor. There are various sensors can be used to implement an electrical current instrument. Resistive current sensing (shunt) is a high accuracy method due to direct contact between a sensor and signal conditioning block, which also may cause voltage drop (loading effect) due to the lack of isolation between the blocks. In this case, the non-contact option is a more reliable choice.
to avoid direct contact between the measured current and the instrument. Several options such as magneto-resistive, current transformer and Hall-effect sensor are available [5].

Hall effect sensor is a relatively simple sensor that suitable to measure high magnitudes of DC current because the geometrical nature of sensor mechanism which needs a cross-sectional magnetic field to the sensor, as mainly high DC current over a wire generate circular geometry around a wire. The magnetic field can then be concentrated into the sensor by using several concentrator materials such as FeSi, FeNi and 1010 steel with the typical geometrical form of concentrators in the shape of the ring and rectangular metal around the conducting wire (as measurement object) [6, 7].

A previous study on the electrical current measurement using Hall effect sensor was developed in an open-loop configuration type of signal conditioning circuit [8]. In an open-loop type the detected Hall potential was directly used as the main signal as the representation of the measured electrical current along the conducting wire. Another study, [9] showed that the open loop system relatively susceptible for the deviation, therefore the accuracy of the most open loop configuration of Hall effect sensor is around 1% of full scale, while the open loop configuration accuracy can reach around 0.5 % of full scale. In the same study, the authors also introduced the optimization of the load resistance and the error compensation method for increasing the accuracy of the closed-loop configuration of Hall effect sensor.

In the previous study, the focus mainly deals with the accuracy of the low current measurement. In the current study, an implementation of the method described in the reference [9, 10] was applied to measure high magnitude DC current, thus the block evaluation was performed and the result will be discussed.

2. Methods
A closed-loop configuration of Hall effect sensor is an optimization of the signal conditioning to enhance the capability of the Hall effect sensor in handling the deviation error appears in the electrical current measurement. A typical close loop Hall sensor consists of Hall effect sensor, coupled with the amplifier to drive the transistor as the switch of the secondary current from power supply to flow into wire turns, around magnetic concentrator. This method will "reset" the magnetization state in the concentrator material due to the primary measured current, thus making the offset of the Hall potential reduced.

![Figure 1. Schematic design of the high-DC current measurement instrument based on closed-loop Hall effect sensor.](image)

The mechanism is described in figure 1 where the schematic design of the designed instrument was also illustrated. The Hall effect sensor used in this study is SS49E (Honeywell Inc.). The error compensation of the Hall-potential adopted the method described in the literature [9]. In the signal conditioning block, the amplifier was used to synchronize the voltage to fit the scale for data conversion, the output signal was connected to 10 bits-ADC (analog to digital converter) integrated into ATmega
328p microcontroller (Atmel Corp.). The microcontroller managed the data to an LCD display and sent the data to a PC via serial port (FTDI1232). In the PC side, the interface software was developed using Visual Basic (Microsoft Corp.)

3. Result and discussion

3.1. Sensor sensitivity and signal conditioning
The sensitivity of the sensor was obtained at 0.016 V/A at 2.835 V/V gain in the forward direction of current, associated with the possible voltage range in our design (1.164 V to 4.956 V) gives the possible current range to be measured is 0 A to 237 A. In the reverse current direction (negative), the voltage range 1.033 V to 4.509 V associated with 0 A to -174 A by the sensitivity of 0.02 V/A at 2.587 gain. The variation in the gain value is possible due to the tolerance value of the different resistor used in the switch channel. It was found that for the increasing secondary current at 0.01 A, the sensor potential was increasing at 0.0068 V and for decreasing secondary current at 0.01 A the sensor potential was decreasing at 0.078 V. From the number of turns in the concentrator it was known that the 0.01 A in the secondary current will be associated with 1 A of the primary measured current.

3.2. Data conversion and interfacing
According to the calculation, 10 bits ADC with a reference voltage of the microcontroller of 5.17 V gives the ADC resolution at 0.005 V/Data. The values were evaluated by connecting the signal conditioning block to the microcontroller and the microcontroller displayed the converted data to LCD.

![Figure 2](image1.png)  
**Figure 2.** (a) Properties of ADC evaluated by sampling voltage gives the least square fit at \( V_{\text{data}} = 1.01 \ V_{\text{in}} + 0.07 \) and \( R=1 \). (b) Screenshot of interface software during the measurement and data acquisition.

The linearity of the data conversion was observed from the plot in figure 2 (a). The sampling voltage data was converted into digital data and gives the fitting line slope at 1.01, offset 0.07 V and correlation coefficient 1.00.

The developed interface software records the real-time values provided by the microcontroller, the screenshot was presented in figure 2 (b) where the increasing values of the DC current were captured vs. time.
Figure 3. (a) The plot of measured current and given current at increasing step value and decreasing step value, the relative constant difference was observed. (b) At different current region.

3.3. Integrated system performance

The evaluation to all block in the designed system was implemented by current measurement. The result was presented in the plot of figure 3 (a). While the given current was set in 20 A – 50 A range, it was observed that there are different values between increasing "step" of current, compared to decreasing step values of given current. By using the linear fit in both data, the difference can be analysed and it was observed that the difference is relatively constant at this range. This difference described the “as is” values from the developed circuit, the information of the deviation can be used easily for the adjustment/tuning the instrument in the software side (microcontroller and interface software).

The instrument performance was also evaluated in the lower range of the current signal at 1 A - 10 A, the plot was presented in figure 3 (b). In that plot, the direct comparison with the higher range (20 A-50 A) was obvious, the highly linear characteristic of accuracy in the lower current range can still be preserved in the higher current range, and the accuracy seems to be in agreement with the previous study [9]. The correlation coefficient for the plot is sufficiently high at 0.99. Although the instrument was designed to work at full range -169 A – 237 A, unfortunately for the current higher than 50 A still cannot be evaluated due to the unavailability of the current source at that range, it will be tested in the future enhancement and integration to control system in the smart DC-grid monitoring and control system development.
Table 1. The datasheet of developed high DC current instrument.

| Characteristic                      | Biases          |
|-------------------------------------|-----------------|
|                                     | Forward | Reverse |
| Output type                         | Linear   |         |
| Range (designed)                    | 0–237 A | 0–169 A |
|                                    | 1.164–4.956 V | 1.033–4.529 V |
| $\mu_r$ Concentrator               | 63.578   | 84.281  |
| Error                               | 2–13 %   |         |
| Error                               | ±0.313 A | ±0.250 A |
| Sensor voltage sources              | 5 V      |         |
| Voltage supply, Op-Amp              | (+) 12 V & (-) Ground |
| Current transducer resolution       | 0.016 V/A | 0.020 V/A |
| ADC reference voltages              | 5 V      |         |
| Analog to digital reference voltage | 0.005 V/Data |         |
| Offset                              | 1.164 V   | 1.033 V |
| Calibration                         | $V_{\text{offset}}=2.5$ V | $V_{\text{offset}}=2.5$ V |
|                                    | $V_{\text{ref}}=2.1$ V | $V_{\text{ref}}=2.9$ V |
| Linearity (Correlation coefficient) | 0.993    | 0.997   |

The summary of the High DC current instrument characteristic was presented in table 1.

4. Conclusion
The measurement system for high DC current has been developed using closed-loop Hall effect schemes. The system was integrated to the digital block for data acquisition. The Integrated system showed the linear profile of measurement data and designed to operate in the current from -169 A to 237 A range. The measurement deviation of the developed instrument was compensated by a closed-loop Hall sensor configuration followed by offset reduction in signal conditioning block and adjustment in the digital data based on the block calibration and evaluation. The implemented system will be ready to use for the monitoring or control system which deals with high magnitude of DC current such as smart DC grid for house electricity and electric vehicle charging system.

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**Acknowledgments**
The author acknowledges the financial support from Penelitian Pengembangan Unggulan Perguruan Tinggi (PPUPT), Universitas Padjadjaran, Bandung, Indonesia.