UNIVERSITI PUTRA MALAYSIA

BIDIRECTIONAL DETECTION METHOD USING FOUR HALL EFFECT SENSORS FOR WATER FLOW MEASUREMENT SYSTEM

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By

RASOUL GARMABDARI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Degree of Master of Science

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DEDICATION

First and foremost I would like to thank God, my creator, for giving me the intellectual capacity to learn about His creation. Without His gift and grace to me, I could do nothing. I would like to express my utmost appreciation to both of my parents, without whose encouragement I would never have started and without whose support I would never have finished.

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Abstract of thesis presented to the Senate of Universiti Putra of Malaysia in fulfillment of the requirement for the degree of Master of Science

BIDIRECTIONAL DETECTION METHOD USING FOUR HALL EFFECT SENSORS FOR WATER FLOW MEASUREMENT SYSTEM

By
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May 2014

Chairman: Suhaidi Bin Shafie, D.Eng.

Faculty: Engineering

Natural resources are defined as material and components which are derived naturally from environment and they exist in a natural form and undisturbed by humanity. According to the statistical investigations, during the last century, the water consumption has grown two times more than the growth rate of population. Based on these studies, this amount of water is used for different purposes including 70% for agriculture, 20% for industry and 10% for domestic usage. The water management is taken into account as one of the natural resources, which must be managed and it can be achieved by measurement and monitoring the water consumption and water flow, which are considered as crucial issues in industry and domestic usages.

Numerous water flow measurement (WFM) systems have been reported such as Hall-Effect (HE) sensor based WFM systems, which also can be categorized into different types such as single HE sensor, two HE sensors and three HE sensors based WFM systems. However, there are some weaknesses in their measurement techniques such as capability to detect the flow direction, high sensitivity against noise and disturbances signals, low accuracy, and high power consumption. Furthermore, none of them are capable of recognizing the source of occurred error, which makes troubleshooting of these systems a time consuming task, due to necessity to disassemble the system.

The design of the proposed four HE sensors based WFM system can be separated into three main units, including motion sensing unit (MSU), data acquisition and processor unit (DAPU), and measurement and monitoring unit (MMU). The MSU is based on four analog HE sensors and two permanent magnets, which are differentially arranged on rotating disc and fixed plate. This arrangement generates 8 sequential codes that can determine the flow direction and it increases the accuracy of WFM system as well. The DAPU consists of four differential amplifiers, schmittriggers, and voltage level shifters. The configuration of MSU and DAPU is purposely designed to reduce the effects of noise and disturbance signals. Lastly, a measurement and monitoring algorithm is developed based on Labview to calculate the flow rate, water consumption and detect the error source and flow direction. Although, in this research, an artificial turbine is used instead of actual turbine, but their operation principles are similar. A proposed WFM system based on four HE sensors has been designed and implemented. The functionality and performances of the system has been confirmed. The results indicated that the proposed four HE sensors based WFM system is able to measure the water flow rate in both forward and reverse flow direction between 0 to 52 liter/minute and water consumption. Additionally, the flow direction and the error source can be determined based on generated sequential code. Moreover, the noise analysis was performed and the spectral noise density of the designed WFM system was resulted almost 35 nV between 0 to 9 kHz, therefore, the immunity of proposed WFM system against disturbance signal and noise, is confirmed. The power consumption is also reduced by using switch technique by 95.68% as compared with conventional WFM systems. The developed WFM system can be applied in other applications such as oil and gas meters, wind turbine, RPM meter of automobile, automatic meter reading (AMR) systems and any rotary movement based apparatuses.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

KAEDAH PENGESANAN DWIARAH MENGGUNAKAN EMPAT PENDERIA KESAN HALL UNTUK SISTEM PENGUKURAN ALIRAN AIR

Oleh
RASOUL GARMABDARI

Mei 2014

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Sumber asli ditakrifkan sebagai bahan dan komponen yang diperolehi secara semula jadi dari persekitaran dan mereka wujud dalam bentuk semula jadi dan tidak terganggu oleh manusia. Menurut kajian statistik, penggunaan air berkembang lebih dua kali ganda daripada kadar pertumbuhan penduduk di abad yang lalu. Berdasarkan kajian, jumlah air digunakan untuk tujuan yang berbeza termasuk, 70% untuk pertanian, 20% bagi industri dan 10% untuk kegunaan domestik. Pengurusan air diambil kira sebagai salah satu sumber semulajadi yang perlu diuruskan dan ia boleh dicapai dengan pengukuran dan pemantauan penggunaan dan aliran air yang dianggap sebagai isu penting dalam penggunaan industri dan domestik.

Pelbagai sistem pengukuran aliran air (WFM) telah dilaporkan seperti sistem WFM berasaskan penderia Kesan-Hall (HE) dimana mereka boleh dikategorikan kepada beberapa jenis seperti sistem WFM berasaskan penderia HE tunggal, dua penderia HE dan tiga penderia HE. Walaubagaimanapun, terdapat beberapa kelemahan dalam teknik pengukuran mereka seperti keupayaan untuk mengesan arah aliran, kepekaan yang tinggi terhadap hingar dan gangguan isyarat, ketepatan yang rendah, dan penggunaan kuasa yang tinggi. Tambahan pula, tiada satu pun daripada mereka yang mampu untuk mengesan sumber ralat dan ini menjadikan penyelesaian masalah mengambil masa yang lama kerana perlu untuk membuka sistem.

Rekabentuk sistem WFM berasaskan empat HE penderia yang dicadangkan boleh dikategorikan kepada tiga unit utama iaitu unit penderiaan gerakan (MSU), unit pemerolehan dan pemprosesan data (DAPU), dan unit pengukuran dan pemantauan (MMU). MSU adalah berdasarkan kepada empat penderia HE analog dan dua magnet kekal yang diatur pada cakera berputar dan plat tetap. Susunan ini menjana 8 Kod berurutan yang boleh menentukan arah aliran dan juga ia meningkatkan ketepatan sistem WFM. DAPU terdiri daripada empat penguat pembezaan, schmittriggers, dan penganjak tahap voltan. Konfigurasi MSU dan DAPU sengaja direka untuk mengurangkan kesan hingar dan gangguan isyarat. Akhir sekali, pengukuran dan pemantauan algoritma dibangunkan berdasarkan perisian Labview

untuk mengira kadar aliran, penggunaan dan mengesan sumber ralat dan arah aliran. Walaubagaimanapun, dalam kajian ini, satu turbin tiruan dan bukannya turbin sebenar telah digunakan tetapi prinsip operasi mereka adalah sama. Sistem WFM yang dicadangkan berdasarkan kepada empat penderia HE telah berjaya direkabentuk dan dibina. Fungsi dan prestasi sistem tersebut telah disahkan. Hasil kajian menunjukkan bahawa sistem WFM berasaskan empat penderia HE yang dicadangkan mampu untuk mengukur kadar aliran air di kedua-dua arah di antara 0-52 liter / minit dan boleh menyukat penggunaan air. Selain itu, arah aliran dan sumber ralat juga boleh ditentukan berdasarkan kod berurutan yang dihasilkan. Analisis hingar juga telah dilakukan dan nilai ketumpatan spektrum hingar sistem WFM yang direka ialah 35 nV untuk julat frekuensi antara 0 hingga 9 kHz. Oleh itu, imuniti yang tinggi untuk sistem WFM yang dicadangkan terhadap gangguan isyarat bunyi telah disahkan. Penggunaan kuasa juga dikurangkan sebanyak 95.68% dengan menggunakan teknik suis berbanding dengan sistem WFM konvensional. Sistem WFM yang dibangunkan juga boleh digunakan dalam lain-lain aplikasi seperti minyak dan gas, turbin angin, meter RPM kereta, sistem meter pembaca automatik (AMR) dan mana-mana alat yang berputar.

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I certify that a Thesis Examination Committee has met on 19th May 2014 to conduct the final examination of Rasoul Garmabdari on his thesis entitled "Bidirectional Detection Method Using Four Hall Effect Sensors For Water Flow Measurement System" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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DECLARATION

Declaration by Graduate Student

I hereby confirm that:

- this thesis is my original work;
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- ownership of intellectual property from the thesis is as stipulated in the Memorandum of Agreement (MoA), or as according to the Universiti Putra Malaysia (Research) Rules 2012, in the event where the MoA is absent;
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This is to confirm that:

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LIST OF ABBREVIATIONS

AMR	Automatic Meter Reading
ASCII	American Standard Code for Information Interchange
AVc	Common Mode Gain
AVd	Differential Mode Gain
BCD	Binary Coded Decimal
BJT	Bipolar Junction Transistor
BPF	Band Pass Filter
BRF	Band Rejection Filter
C	Centigrade
C.P	Counted Pulses
CAM	Computer-Aided Manufacture
CET	Constant Elapsed Time
CMOS	Complementary Metal Oxide Semiconductor
CMR	Common Mode Rejection
CMRR	Common Mode Rejection Ratio
DA	Differential Amplifier
DAPU	Data Acquisition and Processing Unit
dB	Decibel
DES	Design of Experimental Setup
EEPROM	Electrically Erasable Programmable Read Only Memory
F.R	Flow Rate
FDA	Fully Differential Amplifier
f_{-3dB}	Cut off frequency
HE	Hall-Effect
HPF	High Pass Filter
IC	Integrated Circuit
KCL	Kirchhoff Current Law
KVL	Kirchhoff Voltage Law
LED	Light-Emitting Diode
LPF	Low Pass Filter
LTP	Lower Threshold Point
LVDT	Linear Voltage Differential Transformer
MCU	Micro-Controller Unit
MFR	Mean of Flow Rate
MMU	Measurement and Monitoring Unit
MOSFET	Metal Oxide Semiconductor Filed Effect Transistor
MR	Magneto-Resistive
MRE	Magnetic Rotary Encoder
MSU	Motion Sensing Unit
NMOS	Negative Metal Oxide Semiconductor
OPAMP	Operational Amplifier
P.C	Personal Computer
PCB	Printed Circuit Board
PD	Positive Displacement
PIC	Powdered Iron Core
PMOS	Positive Metal Oxide Semiconductor
P_{Peak}	Peak Power Consumption

RPM	Round per Minute
S.S	Sensor Signal
SCH	Schmittrigger
SND	Spectral Noise Density
SPI	Serial Peripheral Interface
T	Time Period
T_a	Actual Time
T_{off}	Off Time
T_{OLT}	Overlapping Time
T_{on}	On Time
T_p	Processing Time
T_{PHL}	Propagation Time from High to Low
T_{PLH}	Propagation Time from Low to High
TTL	Transistor-Transistor Logic
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus
UTP	Upper Threshold Point
VLS	Voltage Level Shifter
VT	Threshold Voltage
VTC	Voltage to Current Convertor
WFM	Water Flow Measurement

CHAPTER 1

INTRODUCTION

1.1 Overview

The water usage has increased two times more than the rate of global population growth within the last century. According to the statistical studies, the global population is growing by roughly 80 million people annually, representing increased freshwater demand of around 64 billion cubic meters in the same period of time. This amount of water is being consumed in three fields comprising irrigation 70%, industry 20% and domestic usage 10% [1]. Therefore, water flow rate and consumption measurement are considered as essential issues in metering throughout the world due to the fact that most industrial processes utilize large amounts of water for manufacturing and processing operations. Petrochemical, metallurgical, pulp and paper industries, for examples, are instances of such operations. Aside from the above, natural resources management and conservation have been the main spotlight globally and is believed to be critical due to limitations in their reserves. Hence, measuring the amount of water that is used during production and supply is often a crucial component of managing the processes. Similarly, measuring the volumes of effluent that are released to the environment is also essential to enforcing regulations [2].

Basically, flow measurement is defined as the quantification of bulk fluid movement and it can be measured in gallons per minutes (U.S. unit) or liters per minutes. Flow meters are also devices that can measure the amount of liquid that passes through them. The volumetric flow rate, (also known as volume flow rate, rate of fluid flow or volume velocity) is the volume of fluid, which passes through a given surface per unit time. The SI unit is m^3/min (cubic meters per minute). In US Customary Units and British Imperial Units, volumetric flow rate is often expressed as ft^3/min (cubic feet per minute) [3, 4]. The basic diagram of a flow measurement system is shown in Figure 1.1.

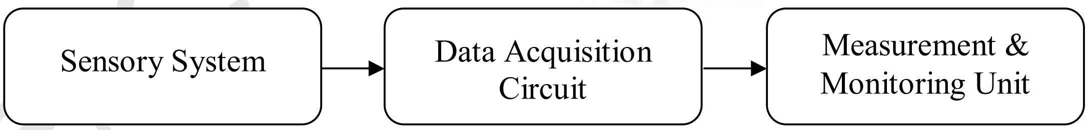

Figure 1.1. The basic diagram of water flow measurement (WFM)

Various methods and systems have been reported for measuring the water flow rate. Optical [5] and mechanical mechanisms, for examples, are the practical approaches for the flow rate measurement. Ultrasonic [6], capacitive [7] and electromagnetic [8] also have been actively researched in the recent years. The rotary encoders are also considered as a type of electronic flow meters, which have been developed to measure the water flow rate of rotary mechanism based systems.

In order to realize the value and importance of rotary encoders in flow rate measurement applications, many techniques and apparatuses have been developed based on various types of sensors such as, magnetic [9, 10, 11] optical [12], capacitive [7], and ultrasonic [13]. The rotary encoders are evaluated in terms of accuracy, sensitivity to environment conditions, and power consumption according to desired application.

The angular and linear motion detectors are counted as fundamental functions in a large number of machines, robots, peripheral computer input devices, water flow measurement and a wide range of instruments. Though, there are a variety of techniques to measure the angular and linear motion, their simple method of connecting to digital systems has made them very common and popular. Magnetic rotary encoder (MRE) is a well-known type of angular motion detector.

The operation principle of a MRE based water flow meter, is the detection of variable magnetic field produced by either permanent magnets or electromagnets, which are disposed on the revolving object. The revolving object is also connected to the rotary shaft. The shaft is coupled with either a mechanical mechanism or a direct connection to a turbine in contact with fluid. The sensing element can be any type of magnetic sensor to detect the magnetic field variation, such as hall-effect sensor (HE), magneto-resistive sensor (MR) [14], linear voltage differential transformer (LVDT) [15] or even a simple inductor. The sensors are disposed in a fixed part to sense the uneven magnetic flux. Thus, the frequency of magnetic flux changes is directly proportional to the velocity of the revolving shaft.

The HE sensor is one of the high performance sensing elements, which is capable of detecting the existence of extreme magnetic fields and measuring them. HE sensors are available in the market in low price. They are applied in a wide range of applications such as proximity switching, angular positioning, measuring rotational speed, controlling magnetic doors, ferromagnetic surface evaluation, current measuring, inspecting material, finding leakage though pipelines, etc. Thus, HE sensor are widely used to detect the magnetic field in both angular motion or linear motion detectors [16].

Basically, the HE sensors are utilized in a rotary encoder as a precise device to measure the distribution of magnetic field of the magnetized elements installed on a disc, which is coupled with a rotary shaft. However, a single HE sensor is limited to measuring accurately and sensing the magnetic field intensity in a near region to the magnetized element. Moreover, it is impossible to detect the direction of rotation using a single HE sensor. Thus, in most of rotary encoders, more than one HE sensor or actuator are applied in order to measure the speed, detect angular position and detect the direction of rotation [16].

In aspect of the effectiveness of HE sensors in flow measurement systems, many types of H.E rotary encoders have been reported for measuring the flow rate, consumption, and passing direction of fluid. D. Winter et al invented the water meter based on two H.E sensors embedded on stationary part and permanent magnets as actuators [17]. A. Hendey et al developed a water meter based on three hall-effect sensors and one permanent magnet as their actuator [18]. L.W. TomcZak et al designed an angular position transducer using permanent magnets and H.E sensor as actuators and sensing element, respectively [19]. D. L. Kordecki et al developed a new technique to detect the angular rotation of a shaft based on a H.E sensor and a disc shaped magnet with four polarities [20].

1.2 Problem statement

There are various types of flow measurement apparatus, which are classified in two main groups: the mechanical [21] and electronic meters. Recently, electronic flow meters are more effective for flow measurement than the mechanical meters due to lower depreciation during long time, more accuracy, and higher capability to implement automatic meter reading (AMR) instead of human reading, which will lead to reduce the human fault during measurement monitoring [22].

Although, many different systems are employed in electronic flow meters such as electromagnetic [23], ultrasonic [6], different pressure based, vortex flow meter [24], but the implementation and calibration of rotary encoder based electronic flow meters such as HE based rotary encoders are less complicated as compared to other systems [25]. Consequently, Rotary encoder based WFM systems can be utilized not only in industrial, but also in domestic applications.

In comparison with the other types of angular encoders such as optical [12], capacitive [7], ultrasonic [26], and mechanical based encoders, magnetic rotary encoders (MREs), especially HE rotary encoders have much lower dependency on the environment conditions such as dust, mist, light, vibration, and humidity [27, 28, 9]. Besides, the HE rotary encoders consume less power than the other mentioned types of encoders [29, 30, 27]. Generally, the HE encoders are based on the sequence of created digital codes [17]. Basically, the HE rotary encoders are used to detect the angular position of the rotary shaft or the number of complete rotations [31].

There are single [32, 33], two [8], and three HE sensor based [17] rotary encoders, which are available in markets and capable of measuring the water flow rate. Water flow detection, which is taken into account as one of the most important properties of WFM systems has the ability to detect the flow direction through the WFM system and they are known as bidirectional WFM systems. However, the single HE sensor based WFM system is not capable of detecting the flow direction and it is called unidirectional and there is no data security in two and three-hall sensor based WFM systems. More importantly, these systems have no immunity against disturbance and noise signals, therefore, they are normally used in domestic applications. In previous designs [19, 20, 25, 27], if any error occurs in HE sensor based rotary encoder, the system must be dissembled to find the source of fault, which is a time consuming task. Meanwhile, as mentioned above, the WFM systems, which are based on the other types of sensors, such as optical [27], ultrasonic [6], capacitive [7], electromagnetic [23, 8], consume higher power for their operations compared with HE sensor based WFM systems. Lastly, the accuracy of previous art of HE rotary encoders is low, because it is just able to detect a complete rotation, while the proposed HE based rotary encoder can double the accuracy.

The above mentioned weaknesses of existing HE rotary encoders serve as motivations to design and develop an improved sensor based device and a method for measuring the flow rate and consumption of fluid, based on the effect of varying magnetic flux distribution at HE sensor's output. Thus, sensor arrangement and interface circuit should be designed in order to eliminate the disturbance and noise signals, increase the accuracy compare to previous art and automatically recognize the fault.

1.3 Objectives of Research

The aim of this research is to design and develop a WFM system, which is based on HE rotary encoder, while avoiding the difficulties in the prior arts. The major objectives of this research are listed as follows:

i) To design and develop a four HE sensor based rotary encoder for WFM system.

ii) To design and develop a low noise interface circuit and monitoring algorithm to process the data and display the water flow rate and consumption graphs, as well as indicating the flow direction and recognizing the fault source.

iii) To optimize power consumption of the WFM system.

1.4 Scopes of Research

This research concentrates on design, development and performance analysis of the WFM systems based on four sensor HE rotary encoders. The designed and developed WFM system is capable of measuring and displaying the flow rate, consumption, direction of flow and the source of fault in industrial and non-industrial environments. This research is composed of three main stages, including design and development of a four-HE sensor based sensory system, design and development of a data acquisition and processing circuit, and development of a flow rate measurement and monitoring algorithm.

The motion sensing unit (MSU) is involved with designing the motion sensing unit for different types of WFM and then it is specialized for HE rotary encoders, in which HE sensors and permanent magnets are employed as sensing elements and actuators, respectively. In this unit, four sensors are embedded in 180 degree angular distance in two complementary groups in order to remove the disturbance signals. These sensors are arranged in a way that 8 sequential situations are generated within 360 degree rotation; therefore, the direction of system is also detectable.

The second unit is involved with designing data acquisition and processing unit comprising analog readout circuit, digital interface circuit (for processing the collected data), and data transmitter circuit. The analog readout circuit consists of four differential amplifiers connected to the outputs of sensors. The two sensors in every complementary sensor groups are differentially connected into differential amplifiers. The output of these amplifiers needs to be converted to digital level and then four schmittriggers are utilized for this purpose. After converting the signals of the sensors to digital data, a microcontroller algorithm is required to detect the sequence of generated codes, which can determine the angular position, direction and the occurred error of the rotary encoder. After processing the generated codes, some information such as the number of rotation and the error code need to be transmitted to the measurement and monitoring unit (MMU), using a serial to USB transmitter.

Finally, the third unit is involved with implementing the calculation and monitoring algorithm into processing and display software based on Labview. Basically, there are different techniques to measure the velocity or flow rate of water. In this research, due to its accuracy in low and high speeds, the constant elapsed time method is used to measure the flow rate. In this research, an artificial turbine is utilized instead of actual turbine in order to evaluate the system performance in different flow rates, changing the direction of flow, fault recognition capability and extraction of statistical water flow and consumption information, which can be useful for water distribution companies.

1.5 Limitation of Research

There are two limitations in experimental results of this research, including the following:

i) Evaluation of practical noise analysis of the designed WFM system in MSU and DAPU is limited because of the inaccessibility to noise figure analyzer.

ii) Fabricating an actual turbine to embed the developed HE based sensory system is difficult and time consuming.

In this research, the noise analysis for the designed electronic circuit of WFM system is performed by using simulation software, in order to overcome the first limitation. In addition, an artificial turbine is utilized instead of actual turbine.

1.6 Research contributions

In order to overcome the weaknesses of reported techniques to measure water flow rate in section 1.2, this research is conducted to efficiently reduce the effect of disturbance signals and noise on the performance of the WFM systems. Therefore the proposed WFM system can be used in industrial applications and noisy environments. Furthermore, the proposed system is designed to automatically detect and display the source of the fault in system. In addition, the power consumption of the system is effectively reduced.

1.7 Thesis Outline

This thesis is arranged in five chapters. The first chapter provides a general overview about the importance of WFM systems and a brief introduction to different techniques of WFM systems and then it is specifically narrowed to the HE rotary based WFM system. In the next section of this chapter, the problem statement on current HE rotary based WFM systems is presented, which has motivated the development of the prototype of four HE sensors based WFM system. Additionally, this chapter clearly describes the objectives to be met as the result of this research and then explains the scopes of this study. The limitation and outline of the research were explained as the two last sections of the first chapter.

The second chapter provides the literature review for different techniques of WFM systems and a comparison between them. Then it focuses on different rotary encoders and then, it is narrowed down to HE rotary encoders. Lastly, this chapter provides a background on HE sensors and their conditioning circuit for different types of HE rotary encoders.

The third chapter encompasses the applied methodology to develop the prototype of HE rotary encoder base WFM system. In the first section of this chapter, the operation principle of HE rotary encoder based WFM system is explained. Then the overall design and the applied method for developing the motion sensing unit (MSU), data acquisition and processing unit (DAPU), and measurement and monitoring unit (MMU) to build up a WFM system are described in this chapter. Lastly, the design of experimental setup (DES) for the purpose of functional evaluation and performance analysis of the developed WFM system is presented.

The fourth chapter covers the discussion on the experimental and simulation results of the developed HE rotary based WFM system. This chapter includes the illustration of flow rate and instantaneous consumption graphs. In addition, it represents the front panel of calculation and monitoring program based on Labview which contains the mentioned waveform charts, flow direction and fault recognition indictors, as well as the required setting options. Moreover, this chapter indicates the noise analysis and simulation results of designed analog readout circuit based on the experimental outputs from MSU.

The fifth chapter summarizes the overall findings of the current research and provides recommendations for the future work for WFM systems. This chapter includes two parts: conclusion and future work, which both of them are based on the achieved experimental and simulation results of the proposed HE rotary encoder based WFM system.

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