Simulation Model Development for Electric Machines and Drives: Rotor Angle and Position Measurement: Modeling and Simulation of Encoder and Encoder Based Position Detector

By

YOHANNES NAKACHEW ZEWODIE

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

COMMUNICATION ENGINEERING STREAM

ID No: ATR/9622/09

Under the supervision of

Prof. Heath Hofmann

UNIVERSITY OF MICHIGAN

DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

Final Internship Report

Hosting Company: University of Michigan

(From June 1, 2021 - October 2, 2021)

Advisor: Tizazu Bireda

Submission Date: February 25, 2021

Declaration

I, Yohannes Nakachew, hereby declare the presented report of internship paper titled "Simulation Model Development for Electric Machines and Drives: Rotor Angle and Position Measurement: Modeling and Simulation of Encoder and Encoder based position Detector" is uniquely prepared by me after completion of the 4-month internship at University of Michigan, African Undergraduate Research Adventure (AURA) program. It is submitted to Addis Ababa Institute of Technology. It is done based on the training I experienced during my stay at AURA program from June 1 to October 2 under the aegis of Professor Heath Hofmann.

Finally, I want to strongly state that the effort I made to manage the gabs between the theoretical and practical world and on the whole project done was in masses.

Name Signature

Yohannes Nakachew .....

Approved by:

Advisor name: Tizazu Bireda

Signature:.....

Acknowledgment

My very first gratitude goes to the almighty God who helped me in each and every move I stepped. The whole work wouldn't be accomplished without him. Then I express my deepest gratitude to Professor Heath Hofmann (Ann Arbor, Michigan, USA) for the sincere motivation and patience. He helped me by sharing files to read and lectures on basic understanding of the research project. He continuously checks on me if I have any confusion and question with the research project, he used to give me.

Foremost, University of Michigan is the next body that deserves the gratitude for setting up such a program for me. But my sincere and special thank goes to AURA organizers Professor Valeria Bertacco, Professor Todd Austin and Magdalena Calvillo for continuously check on me if I have any confusion with the training.

My AAIT mentor Dr. Fitsum Assamnew Andargie support was also impeccable. I am thankful for him. He motivates me and helped me on giving suggestions on the program. So, I want to thank him enough for his continuous support.

Last but not the least; I thank my families for the special comfort they gave me while I work on my paper.

Executive Summary

The internship semester I spent on those 4 months was fruitful. University of Michigan is the institution name that hosts me. The program name is African Undergraduate Research Adventure (AURA). I heard about this program from AURA 2019 participating students at the workshop held at Addis Ababa Institute of Technology. We were 16 AAiT students participating on this program in 2020. The research projects were categorized under different engineering departments such as Computer Science and Engineering, Electrical and Computer Engineering, Mechanical Engineering and Civil Engineering. I was working in the Electrical and Computer Engineering research project during my stay at AURA 2020. I involved in one of the projects handled by Professor Heath Hofmann. It was simulation model development for electric machines and drives. We made Simulink models for Encoder and Encoder based position detector that are used for Rotor Angle and Position Measurement. Many challenges were faced on the project and the whole internship period as well. But smart measures could be taken and solve the challenges occurred. For AURA to make its program more effective it should have more students to work on its research projects and encourage interns more by giving them projects to add up the knowledge an intern could have. As an intern, I benefited a lot from the experience I gained from AURA program. I got knowledge that helps me to visualize the theories I have been learnt on the past 4 years. Besides, I developed lots of interpersonal skills, teamwork skill and problem-solving skill. I was also able to boost the confidence I have already.

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CHAPTER ONE

An Overview of University of Michigan, AURA

Brief history of the company

Today, the University of Michigan remains one of the most distinguished universities in the world and a leader in higher education. It is consistently ranked among the nation's top universities, with over 51,000 students and 5,600 faculty at three campuses. The University of Michigan boasts of one of the largest health care complexes in the world, one of the most extensive university library systems in the country, and the some of the best computer access for students and faculty of any campus in the world. Over 5,500 undergraduate courses are taught each term in over 200 programs. Undergraduate, graduate and professional students have a choice of 19 separate schools and colleges, hundreds of majors, over 1000 student organizations, and thousands of concerts, recitals, speakers, symposia, films, and readings each year.

The students at the University of Michigan come from all 50 states and over 100 foreign countries. Michigan's teaching and research staff is considered one of the top five faculties in the country. They have included an astronaut, distinguished world authorities, Pulitzer Prize winners, internationally acclaimed performing artists and composers, Supreme Court Justices, best-selling novelists, artists, and filmmakers. Michigan has more than 100 named endowed chairs.

Michigan receives over $700 million in research expenditures annually. The diversity of the University's research activities, from medical to social to cultural, is a major contributor of Michigan's capacity for growth and development. And, through their teachers, Michigan students are often among the first to learn the applications of such research findings.

The African Undergraduate Research Adventure (AURA) program is a research exchange program at University of Michigan for undergraduate students at the Addis Ababa Institute of Technology (AAiT). Selected students go to Ann Arbor for twelve weeks during the summer

to engage in research work with a College of Engineering faculty member. The purpose of this program is to engage AAiT undergraduates specializing in the fields of Electrical, Computer, Robotics, Civil, Environmental or Mechanical Engineering in summer research. Eligible individuals should have completed the 4th year of their undergraduate studies. Individuals selected for the program will spend the Summer (mid-May to mid-August) in Ann Arbor, Michigan (United Stated) conducting research with a University Michigan's faculty in their lab.

In 2019, ten students completed the program, having worked with faculty advisors on projects in software engineering, electrical engineering, and mechanical engineering. They celebrated their accomplishments at a reception and poster session that was attended by Alec Gallimore, Robert J. Vlasic Dean of Engineering, Richard F. and Eleanor A. Towner Professor, and Arthur F. Thurnau Professor; faculty advisors; friends; and other supporters. The event was held in Tishman Hall, in the heart of the Bob and Betty Beyster Building, on August 6.

The University has had a long-standing commitment to global engagement," says Arthur F. Thurnau Professor Valeria Bertacco, one of the AURA program's organizers. "The idea of AURA is to bring students from AAiT in Ethiopia to Ann Arbor for the summer to be embedded in a research experience."

She adds that the ultimate goal of AURA is "to create collaborations between UM faculty and AAiT students, which could lead to a range of research collaborations, including applications to our doctoral and master's programs."

Prof. Todd Austin, also an organizer of the AURA program, adds that "I find that when Michigan faculty engage with colleagues at Ethiopian universities, they find friends and colleagues that become a part of their research pallet."

In 2020, 16 students completed the program, having worked with faculty advisors on projects in computer science and engineering, electrical engineering, civil engineering, and mechanical engineering. Because of the COVID-19 pandemic the AURA 2020 program was

accomplished virtually. we celebrated our accomplishments in an online session that was attended by Dean Alec Gallimore, AAiT Executive Director Esayas Gebreyohannes; faculty advisors; friends; and other supporters. The event was held in zoom meeting, on October 2.

AAiT undergraduates are required to develop a thesis to complete their degree – their entire fifth year is dedicated to it. The AURA program is a key opportunity for us to bootstrap this thesis work.

Vision

Michigan Engineering aspires to be the world's preeminent college of engineering serving the common good.

Mission

Michigan Engineering provides scientific and technological leadership to the people of the world. We seek to improve the quality of life by developing intellectually curious and socially conscious minds, creating collaborative solutions to societal problems, and promoting an inclusive and innovative community of service for the common good.

Values

In pursuing our vision and mission, members of the University of Michigan College of Engineering community will value:

Leadership and Excellence

True to being "Leaders and Best," we do not settle. We forge paths that inspire others, and push relentlessly for quality and preeminence in all we do.

Creativity, Innovation and Daring

"We've always done it this way" is never how we do it. We seek to improve the quality of life. Bold thinking and non-traditional action are among the tools we rely on to solve problems and create opportunities.

Diversity, Equity and Social Impact

The best mix of talent achieves the greatest outcomes. People with different skills, backgrounds, identities and perspectives are necessary for us to realize our vision. Opportunities are created for all, and where barriers exist, we close the gaps. Every member of our community gets to be heard, should be involved and must be empowered to achieve to their full potential. We serve the common good.

Collegiality and Collaboration

Camaraderie is a strength. When we disagree, we remain civil. We succeed in facing complex challenges by working together — across the lab, classroom or globe. Teamwork is fundamental to how we operate. We cannot fulfill our potential unless we are combining our strengths. Our individual abilities are joined to accomplish a united vision and mission.

TRANSPARENCY AND TRUSTWORTHINESS

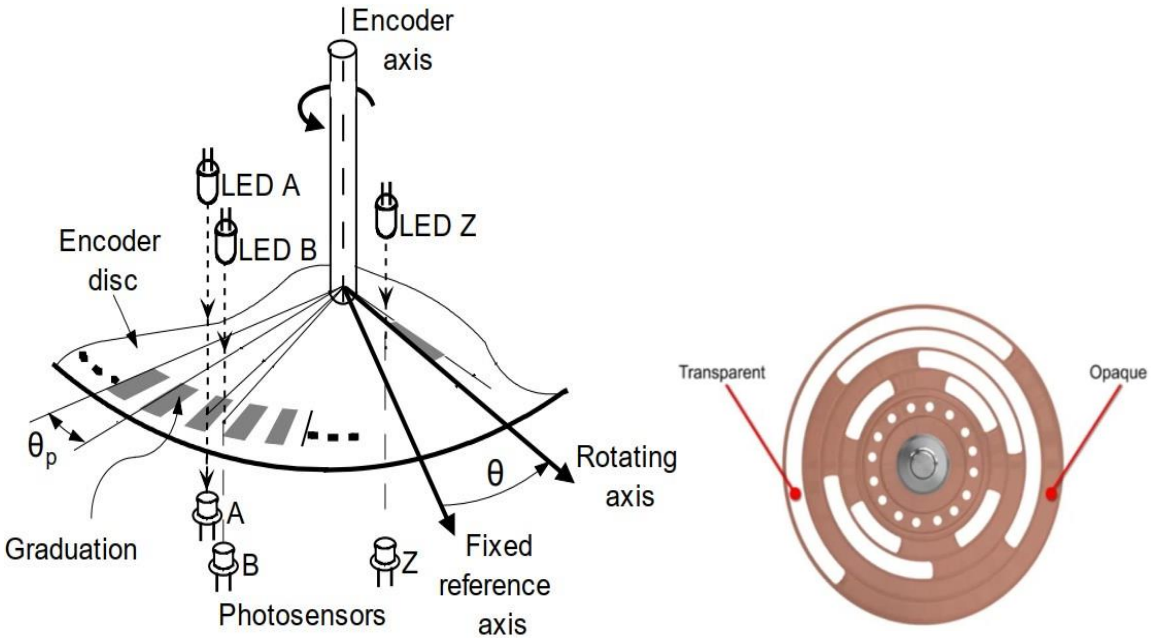
A consistent respect for truth breeds good, lasting relationships. We depend on open and honest sharing of data, facts and individual perspectives. In difficult situations, where discretion is required or conversations are sensitive, we acknowledge the limits of what can be shared. Trust must be preserved.

CHAPTER TWO

Work Piece or Work Tasks I Have Been Executing

2.1 Incremental encoder modeling

The incremental encoder is a device which provides electrical pulses if its shaft is rotating. The number of the generated pulses is proportional to the angular position of the shaft. The incremental encoder is one of the most frequently used position transducers. The principle of an optical incremental encoder is presented in Fig. 1. Together with the shaft there is rotating a transparent (usually glass) rotor disc with a circular graduation-track realized as a periodic sequence of transparent and non-transparent radial zones which modulates the light beams emitted by a light source placed on one side of the disc on the fix part (stator) of the encoder. On the opposite side the modulated light beams are sensed by two groups of optical sensors and processed by electronic circuits. Each of the two outputs of the encoder (noted A and B) will generate one pulse when the shaft rotates an angle equal to the angular step of graduation θp, i.e., the angle according to one successive transparent and non-transparent zone. The number of pulses (counted usually by external electronic counters) is proportional to the angular position of the shaft. Due to the fact that the light beams are placed shifted to each other with an angle equal to the quarter of angular step of graduation $\theta p/4$, the pulses of the two outputs will be also shifted, making possible the determination of the rotation sense. A third light beam is modulated by another track with a single graduation. The output signal (named Z) associated to this third beam provides a single pulse in the course of a complete (360°) rotation. The shaft position corresponding to this pulse may be considered as reference position. Fig. 2 shows the output pulses of the encoder. Usually for counter-clockwise (CCW) direction θ is considered as positive, and for clockwise (CW) direction it is considered negative.



a) *b)*

Figure 1: a) Construction principal of an encoder: b) the gray surfaces are optically transparent Encoder disc

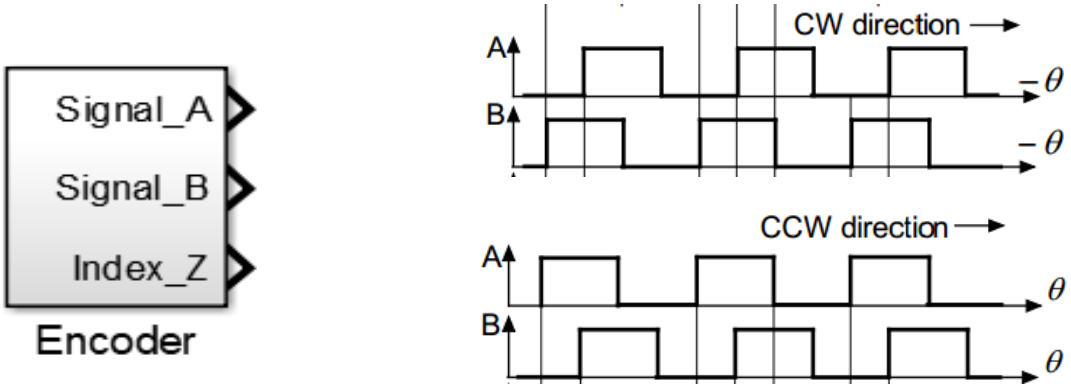


Figure 2*: Diagram of the output signals for counter-clockwise (CCW) and clockwise (CW) rotation.*

2.2 Encoder modeling

The input signal of the encoder is the angular position θ of its shaft with respect to the fixed reference axis. The output signals are the two pulses shifted by 90° A(θ) and B(θ), respectively the marker signal Z(θ). If θ_p is the angular step of the encoder, a mathematical formula relating θ_p with number of bits is:

$$\theta_p = \frac{360x2}{2^{Nb}},$$

where N_b is number of bits

The outputs may be described by the following equations:

$$A(\theta) = \begin{cases} 1, if & 0 \le (\theta \bmod \theta p) \le \theta p/2 \\ 0, if & \theta p/2 < (\theta \bmod \theta p) \le \theta p \end{cases} \quad (1)$$

$$B(\theta) = \begin{cases} 1, if & 0 \le ((\theta - \theta p/4) \bmod \theta p) \le \theta p/2 \\ 0, if & \theta p/2 < ((\theta - \theta p/4) \bmod \theta p) \le \theta p \end{cases} \quad (2)$$

$$Z(\theta) = \begin{cases} 1, if & \theta \bmod (2\pi) \le 1 \ or \ \theta \bmod (2\pi) \ge 359 \\ 0, & Otherwise \end{cases} \quad (3)$$

The number of pulses, generated by the encoder in the course of a rotation, is equal to two the power of number of bits minus one.

$$N_p = 2^{Nb-1}, \text{ where } N_p \text{ is number of pulses} \quad (4)$$

Based on (1), (2) and (3) a MATLAB/Simulink® a simulation structure shown in *Figure. 3* was built. The outputs A, B and Z are computed based on (1) shown above. N_b (number of bit) is

defined by a constant block. The structure is saved as a subsystem. The simulation structure of the encoder may be integrated in any other Simulink® structure

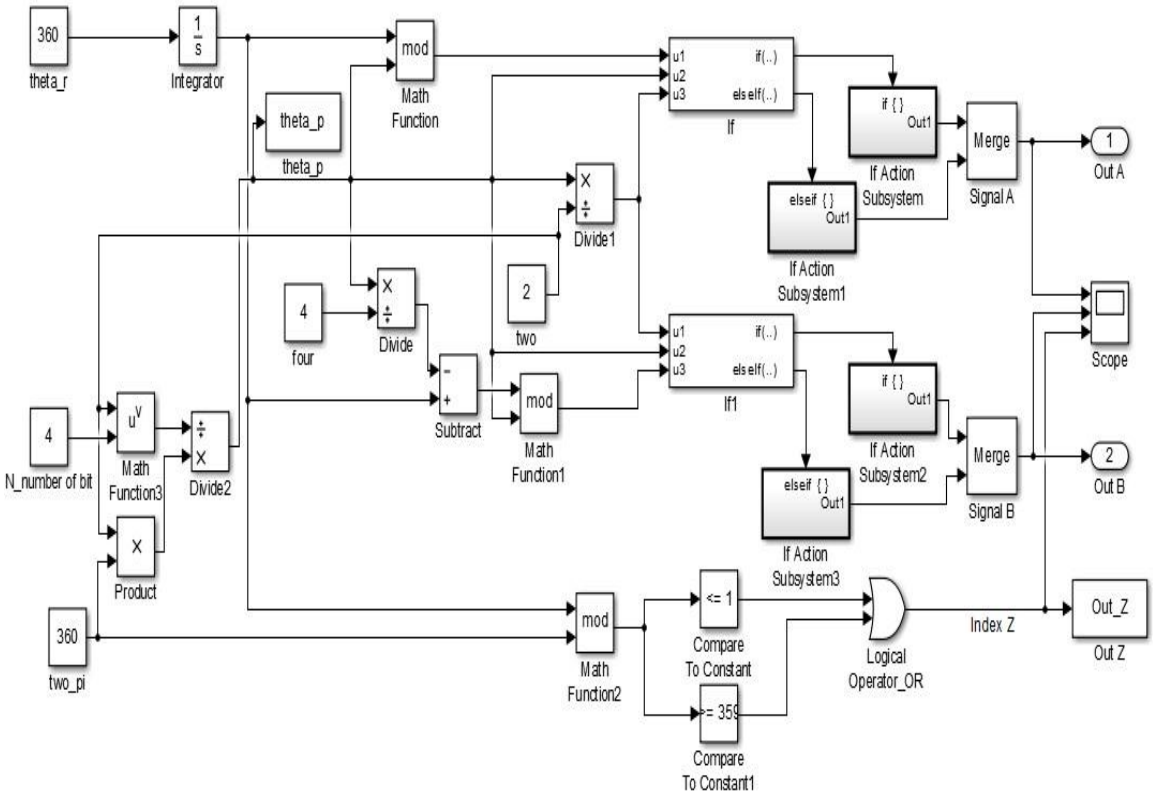
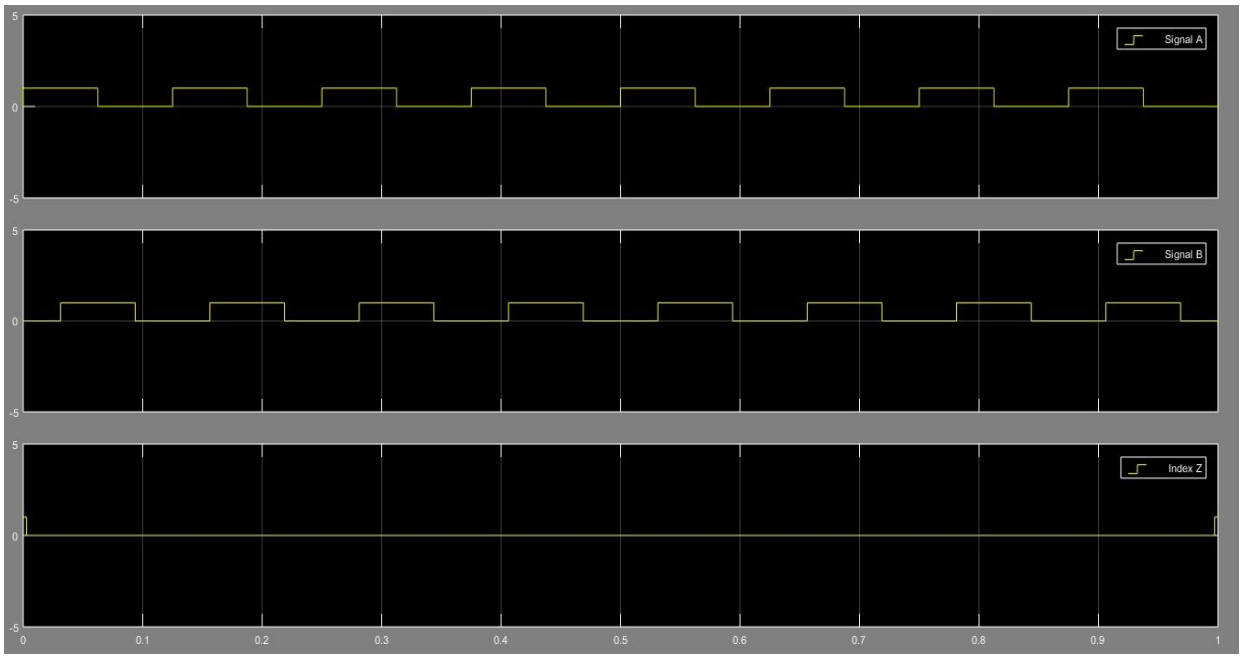


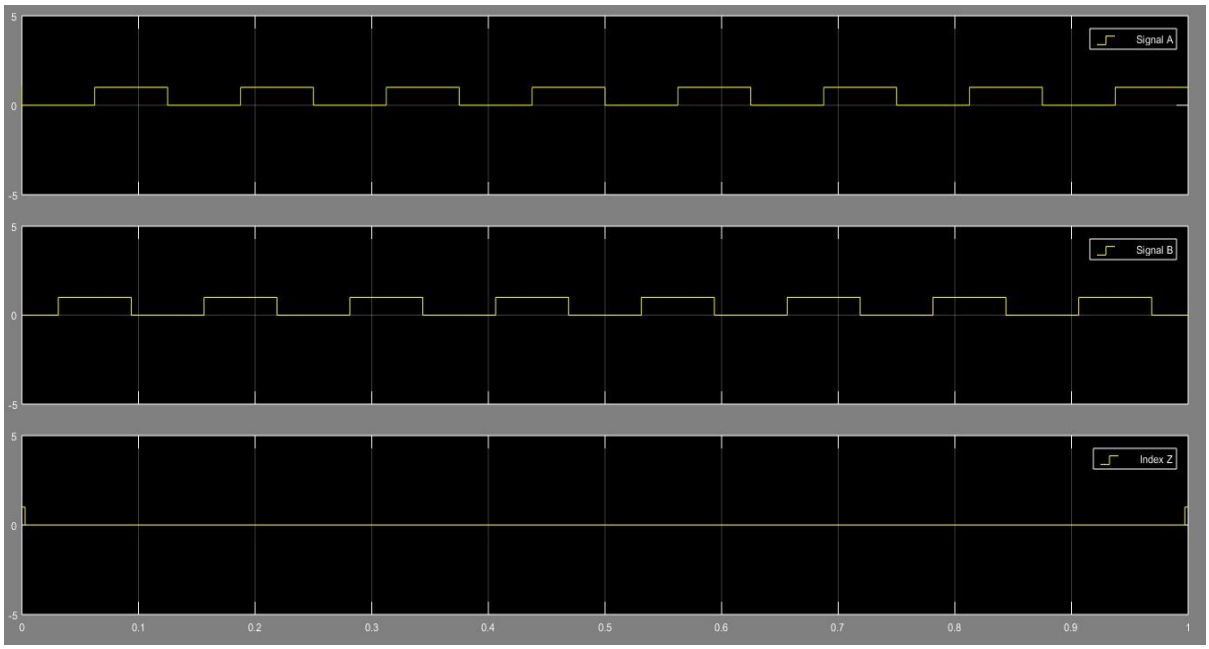
Figure 3: Simulation structure of an encoder.

Simulation results

The structure of the encoder model for simulation is shown in *Figure. 3* above. The input signal of the encoder is generated by a constant block and changed the time to one sec. The encoder generates the A, B and Z signals. In order to test the structure, the constant block theta_r is 360 and some positive number is entered to the number of bit constant block in order to start the simulation generating the A, B and Z signals of the encoder in counter clock wise (CCW) direction. When the input angle theta_r is changed to negative the encoder results in A, B and Z signals of the encoder in clock wise (CW) direction. The simulated results are presented in *Figure. 4. a) and b).*



a)



b)

Figure 4: The A, B and Z signals of the encoder a) in CCW direction, b) in CW direction.

The structure presented in *Figure. 3* may be integrated in the simulation structures of electrical drives [5]. In this case the input signal of the encoder – i.e., the angular position – will be provided by the mathematical model of the electrical machine.

The conditions used in simulations are: N_b = four and the simulation step was taken one sec.

2.3. Encoder based position identification

In an incremental-encoder-based system the angular position θ is measured with respect to a fixed reference axis (θ=0 rad.) and it is obtained by algebraic counting of the number of the generated encoder pulses according to the CCW (ΣNi pulses) and CW direction (ΣNi pulses) and multiplying it with the angular step θp of the encoder [2]. Mathematically:

$$\theta = \theta_p \left(\sum_{i}^{Ccw} N_i - \sum_{j}^{Cw} N_{j)} \right) = \theta_{p*N}$$

In order to compute the algebraic number of pulses it is necessary to know the direction of the rotation.

2.4 Identification of the rotation direction

The two $\theta_p/4$ shifted output signals of the encoder contain implicitly also the direction information which may be obtained in different ways.

Taking into account the all four possible combinations of *A* and *B* signals for the reversals, it is possible to detect the direction changing in all cases during a rotation of the minimal detectable rotation-angle-increment $\theta_p/4$. The *Table below* shows the all combinations of signals which detect the reversal of the rotation sense.

From CCW to CW Q=1 to Q=0 (Triggered by R)		From CW to CCW Q=1 to Q=0 (Triggered by S)	
Occurs if		Occurs if	
A	*B*	*A*	*B*
0	0→1	0→1	0
0→1	1	0	1→0
1→0	0	1	0→1
1	1→0	1→0	1

Table 1: Combination of signals Which detect the reversal of rotation

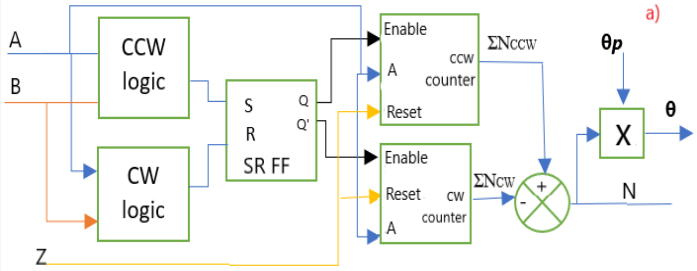


Figure 5: a) The simulation structure of the position computing subsystem

Corresponding to the two possible direction changes the logic blocks detects all combinations of input signals shown in the above Table, the actual combination triggers a flip-flop of which Q output retain the direction of rotation until another changing occurs.

The encoder-output signal A is the common input signal for the two counter blocks: Counter CCW and Counter CW. The counters are resettable by the marker pulse, if the shaft is positioned in the reference position. Both counters receive on their En input distinct "enable to count" signals generated from the "**DiD**" direction detector block according to the detected direction of the rotation. By counterclockwise rotation of the shaft the Counter CCW will be enabled by signal S and will count the encoder pulses A. If the shaft rotates clockwise, the Counter CW will be enabled by signal SN and will count the pulses A. The content of the Counter CW is subtracted from that of the Counter CCW. The difference N will indicate the number of pulses according to position of the shaft. In order to obtain the angular position, the difference N has to be multiplied by the angular step $\boldsymbol{\theta p}$.

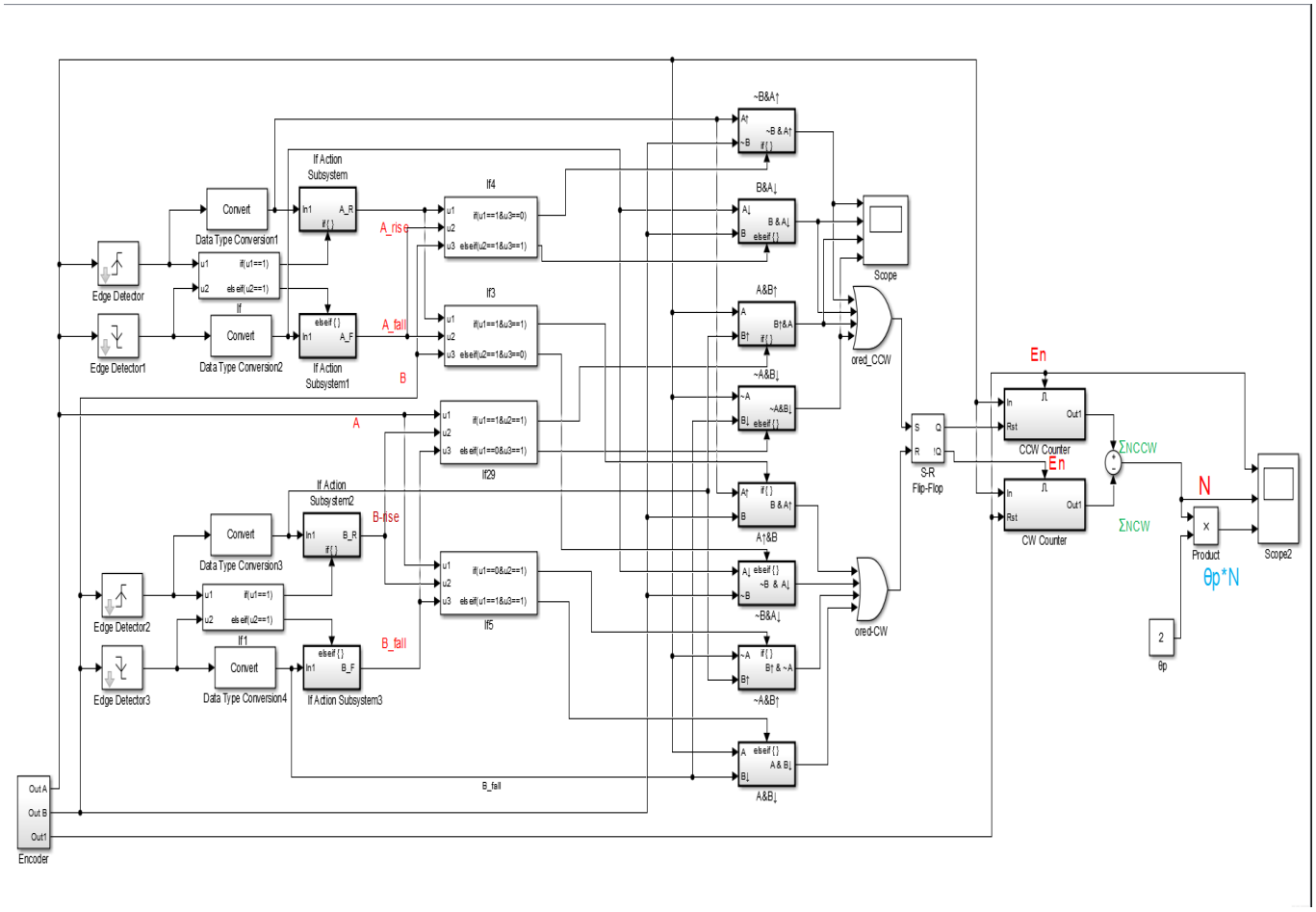


Figure 6: Simulation structure of an encoder-based position detector

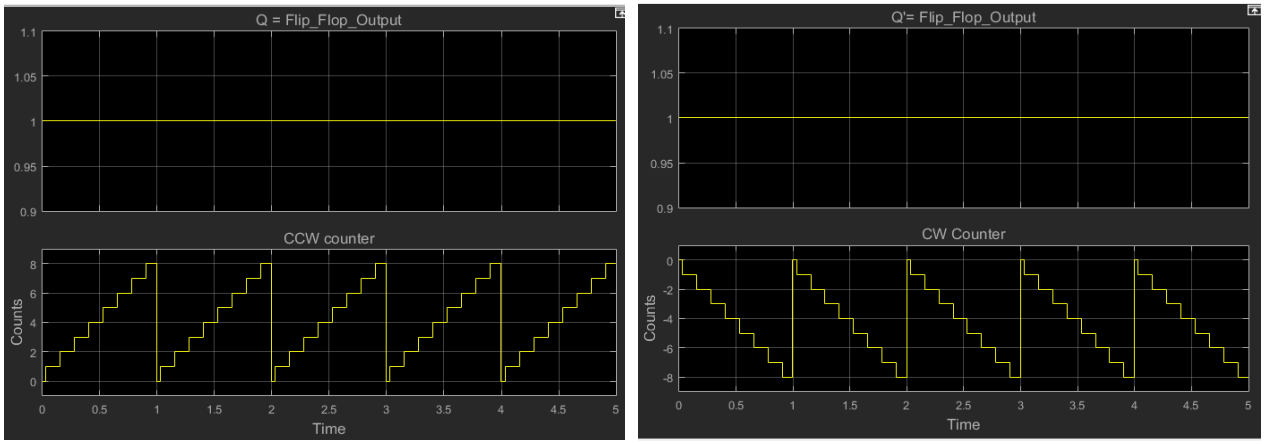


Figure 7: a) **Counter clockwise counter output** **b) Clockwise counter output**

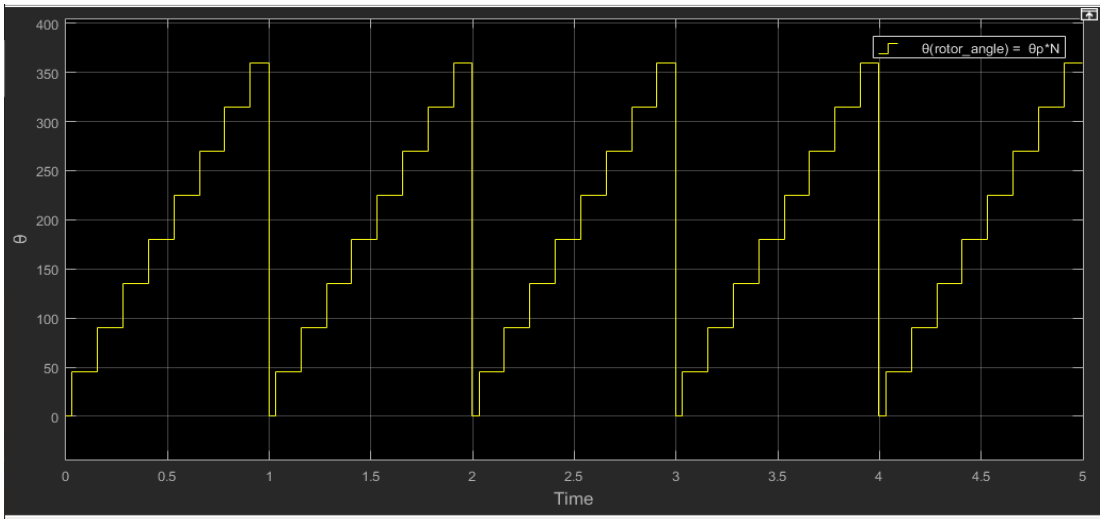


Figure 8: The output of position detector

CHAPTER 4

Challenges and overall benefits gained

4.1 Challenges faced

While I stayed at AURA on these four months, I faced some technical and non-technical problems. The primary challenge was managing the gap between the real work world and the theory we have been learnt in the class room. It consumes a great deal of time to balance the two sides. The absence of taking some required courses for the research program we were going to do and during this program number of problems were encountered. To list some of them;

- COVID-19.
- While I work on the project, there was a power problem while I work and we meet.
- I also had a problem on accessing stable internet connection. It, somehow, disrupt our work plan.
- Difficulties during recording a video for the final presentation

4.2 Measures taken

For challenges mentioned above, measures were tried to be taken to take control over it and for an effective work. For the problem I face on managing the gap between the real work world and the theory we have been learnt in the class room, I asks my mentor for help. Through strong communication with my mentor and through a repeated trial, we were able to get over these technical problems. For the problem we face on recording the video we organize the structure of the presentation and write a script to help prepare what we would say. Since the presentation is limited by time, we had to discuss the main contents that should be included to make our presentation as brief and well-rounded as possible.

We had a dry run presentation to our mentors to get feedback on how we could improve the content of our presentation and address the ideas in a simple and high-level way. We addressed the ideas and did dry runs again to the AURA program organizers and participants to get confirmations for the next step of making recordings. We prepared recordings and got feedback to be addressed.

For the non-technical matters, negotiation was the only option to solve the problem. For internet connection and power problem I used to go out and look for some other place where I can get access to them.

4.3 Over all benefits gained

4.3.1 Theoretical knowledge

The theoretical knowledge I gained during my stay is unlimited. The trainings I took let me to get to know with many computer simulation ideas and design skill. Since the trainings I took were through lecture and hands-on material, I can say I have experienced enough relative to the knowledge that is expected from me. I was equipped with basic and useful skills on the computer simulation area. I was also capable of knowing what visualization on computer simulation area really is.

4.3.2 Practical knowledge

What theoretically learnt is not enough to realize the real work world environment. The computer based practical work I executed during my stay helped on visualizing the theories I knew already. I found myself very much in to the practical work after I once involved in it. A practical work, especially on engineering area of work, is very essential. Looking over the devices used on any work can enhance the understanding and can make the one responsible for the work equipped enough with the ability to clarify what exactly is done. And it helps us to manage and see the theories we know already when it comes down on earth. So, I can say the main skill I got from this internship is my practical knowledge skill. I eventually can get the proficiency to pick up things by myself to solve a certain problem or to create something new on the area I was working on.

4.3.3 Interpersonal communication skills

Communication is a key for a good working environment. The collaboration and interaction with different type of people in AURA helps me love the job I did during my stay. Besides the communication skill I develop, there were many inter-personal skills that I developed in AURA.

- The Self-confidence I developed eventually opens a door and helps me to gain recognition among the AURA coordinators and on other places I went for an intern matter. Beyond this, the confidence I got improves the way people see me, my views and opinions. I start to over show and appreciate my own qualities. After then people start to see them more seriously and appreciate it. It also helps me to deal with challenging situations and allows me to set and reach new goals.
- Work ethics is the other quality I have got on my internship semester. The main work ethics that keeps me to present myself through the discipline and enables me to communicate effectively is the idea of professionalism, dependability, punctuality, respecting one another and team work. These qualities are very essential for having a good working environment. The internship equipped me with these qualities and enhances the ethics I know already as a younger research assistant in the institution.
- Communication is a key to get what you planned to get. The ability in talking with other people helps everyone to see the different perspective human being has on different issues so that to live within the differences. Communication basically helps us to get along with new environments we probably gotten in. After realizing all this benefit of communication in every compound I fix myself to be one of the best communicators to be one of the advantageous interns. And I ultimately could be the intern with the good communication skill.
- In advance with the communication skill I develop, I was also be able to play a team work in any diverse community and environment. I develop other interpersonal skills

along with it like ability to listen to people ideas patiently, respect, self-esteem and respect, dependability and more.

- The team work and communication present in working environment was capable to make me flexible enough to accept a constructive feedback from my colleagues and friends.

All those interpersonal skills I developed on my stay at AURA, honestly helps me to improve my communication skill and able to live my life with a strong sense of purpose and conscience.

4.3.4 Leader ship skill

The way I handle some tasks on the project and my own research as well, provides me with the leadership quality one could develop through the process. I built the ability to motivate, enthuse and build respect among my friends and the persons in the program. The team work on the project manifests my leader ship skill I developed on the process. The credibility I saw, the need how people want to follow me on some specific issues, the motive and the confidence I have on solving a certain problem also proves how I am going on the track to be the accepted and flexible leader.

4.3.5 Sharing

Another quality I developed from my internship is how the idea of sharing helps oneself for self-improvement. Ideas worth sharing for a specific development needed. Sharing is the basic value of AURA. It is highly practiced through many methods. Even though I was an intern ready to receive some knowledge from them, they believe that they can get something new and productive from me. This motive and readiness they have towards discovering new things through sharing while they know many things boost the confidence I have and initiates me to

discover new things daily and share it with them. It also let me to believe and have a positive understanding that everyone else in this world has a creative mind and new ideas to share that enables them to make difference in the planet.

4.3.6 Problem solving skill

Problem solving ability is the other skill I have developed. Each step I have stepped on the track helps me to be capable of solving a certain problem occurred. In collaboration with the above qualities, I developed my problem-solving ability further enhanced. My mind has been adaptive to bring some solution whenever a problem occurs.

4.3.7 Entrepreneurship skill

Since there is a vivid problem of being joblessness these days in our country, I am positive that this skill will surely save me from being one of the jobless graduates. Along the skills of problem-solving ability, leadership and inter-personal communication and understanding the beauty of sharing, I boosted up the creativity ability of my mind to be one of the great men entrepreneurs in the world. And I believe I will be one of them.

CHAPTER 5

COMMENTS, CONCLUSION AND RECOMMENDATION

5.1 Suggestion and comments to the company

During my four months internship program in AURA, I have had a great impact on how my next steps should be like. That is the goal after all, changing one's way of looking things. There are things I know in theory, and there is the real-world according to it. As AURA being a program to engage AAiT undergraduates specializing in the fields of Electrical, Computer, Robotics, Civil, Environmental or Mechanical Engineering in summer research, it should be committed to high-level performance and interns service quality. Excellence and other values it put already should be on action as well. In order to continuously manage the needed improvement, I suggest that the AURA organizers can do the points listed below.

The institution should strongly work on the entrepreneurship and leadership qualities the interns already have. Because it can simply be seen on the achievements the program made on a short period of time with such qualities the interns have. So, it can simply be predicted how great achievements can be met if the institution strongly works on those qualities.

5.2 Conclusion

To conclude what I have experienced and challenged on my internship semester, I can say, the training helps me to be the electrical engineer I dreamed to be. It equipped me with dozens of knowledges on computer simulation through involvement on electric machines and drives Simulink implementation. It let me to know and work with many electrical devices I know already on theories. It also, somehow helped me to develop my MATLAB Simulink skill. The virtualization knowledge I gained can't also be left unlisted.

Since AURA is a program established very few times ago, I can see how a program could be big step by step. I can see the challenges and accomplishment the program face and made as well. So, besides the knowledge I gained, I gained a very great problem-solving skill,

leadership skill and many more qualities. And as I have suggested above, even though AURA program has a good support for intern, there should still be few improvements while working with them. At last, these all achievements are made with the Addis Ababa Institute Technology, University of Michigan, and some people support. My internship semester wouldn't have been successful enough if their contribution wasn't in hand. So, I would like to thank all of them for this once again.

5.3 Recommendation

Under this subsection, recommendation that I strongly believe would bring a change are pointed out.

- I recommend that the company increase its number of interns across other Ethiopian universities. It sees how increasing the number of interns helps a program and its participants to make its work effective on the last year of achievement. By increasing the number of interns, the tendency of adequation of a greater number of students with knowledge and hands-on experience will increase. The flow of ideas will also increase that in return develop the program's status.
- As I have tried to look over AURA's program recognition, people don't know about it. Compared to the work this program is doing and the contribution it is giving to the participating students and this country, it is incredible that it is not well known. So, I recommend that the institution (University of Michigan) and the collaborated institution (Addis Ababa Institute of Technology) should do an advertisement and involve in any events that enables the AURA program to get connected to the people.

References

[1] Heath Hofmann," Electric Machinery and Drives" Department of Electrical Engineering and Computer Science, The university of Michigan.

[2] Incze, I. I., Szabó, Cs., and Imecs, M., "Incremental encoder in electrical drives: modeling and simulation" in *Studies in Computational Intelligence* Editors: I. J. Rudas, J. Fodor, J. Kacprzyk, Springer Verlag, Germany, under press.

[3] Lehoczky, J., Márkus, M., and Mucsi, S., „Szervorendszerek, követő szabályozások", Műszaki Kiadó, Budapest, Hungary, 1977.

[4] https://www.wayneandlayne.com/files/bricktronics/design/optical_encoder_diagram.png

[5] Petrella, R., Tursini, M., Peretti, L., and Zigliotto, M., "Speed measurement algorithms for low resolution incremental encoder equipped drives: comparative analysis", in *Proc. of International Aegean Conference on Electrical Machines and Power Electronics, ACEMP-ELECTROMOTION Joint Conference, Bodrum, Turkey*, 2007, pp. 780.