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# Speed Control of an Electrical Cable Extrusion Process Using Artificial Intelligence-Based Technique

*Robert Agyare Ofosu[1], E. Normanyo[2], N. Abdul-Aziz[2], and S. S. Stickings[3]*

[1] *Department of Control Science and Engineering, Jiangsu University, Zhenjiang, China*
[2] *Department of Electrical and Electronic Engineering, University of Mines and Technology, Tarkwa, Ghana*
[3] *Quality Control Department, Nexans Kablemetal Ghana Ltd, Tema, Ghana*

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CORRESPONDENCE

Phone: +233540358161
E-mail: raofosu@umat.edu.gh

## ABSTRACT

Most cable manufacturing companies use Programmable Logic Controllers with conventional controllers to control line speed during cable extrusion. These traditional controllers have difficulties keeping the line speed constant, causing surface defects on the extruded cables and affecting the quality of the manufactured cables. To overcome these challenges, data on the causes of defects during cable manufacturing were collected from a cable manufacturing company in Ghana to ascertain the possible causes during cable manufacturing. Adaptive Neuro-Fuzzy Inference System (ANFIS) controller was designed to provide a constant line speed during the cable extrusion process. To ascertain its robustness, the ANFIS controller was compared to a conventional Proportional Integral Derivative controller and a Fuzzy Logic controller. The controllers were designed and simulated using MATLAB/Simulink software. The analysis of the collected data indicated that a break in insulation/ sheath was a frequently occurring defect during the cable manufacturing process due to improper line speed control of the machines used in the cable manufacturing process. Based on the results obtained from the various controllers, it was concluded that the ANFIS controller was robust in achieving stability regarding line speed variations.

## INTRODUCTION

Electrical cables are insulated wires or conductors having a protective casing and used for transmitting electrical or telecommunication signals [1]. They have numerous benefits across various domestic, industrial, telecommunications and electronics related applications. The cables are widely used to power electrical appliances or equipment, transmit electric power at different voltage levels for homes and industries. The types of cables normally used depend on the service voltages and rated currents of the circuit [2]. There are different kinds of cables which include single conductor, multiple conductors, coaxial and fibre optic [3]. The conducting part of the cable channels current through the cable while its insulation maintains electricity in the conductor. The conducting part is mostly made of copper due to its high electrical and thermal conductivity, ductility, malleability, solderability, high melting point, high resistance to corrosion and wear. However, aluminum is also used for overhead transmission lines due to its relatively less weight [4].

In electrical cable manufacturing processes, the first stage is wire drawing. Wire drawing reduces thick wire rods into various conductor sizes. The next stage is the annealing process where the wires undergo heat treatment to further increase their conductivity. After annealing, the wires may be bunched together to form a multistrand conductor, preheated and coated with insulating materials such as Polyvinyl Chloride (PVC), Polyethylene (PE) and Cross-Linked Polyethylene (XLPE). The coating stage is attained through a process called extrusion [5]. Extrusion is an essential part of the manufacturing process since it protects the conductor from mechanical damage, environmental hazards and reduces copper losses in cables. After extrusion, the insulated wires cool while passing through a cooling trough and monitored by a gauge to check for the diameter consistency of the insulated cable and spark tester to detect defects in the coating. Finally, the cables are cut into standard lengths, packed into cable coils and made available to customers [1]. A functional diagram of an electrical cable manufacturing process showing the extrusion line is shown in Figure 1 [6].

However, some challenges involved in cable manufacturing include corroding of conductors, cracks, voids, overheating of cable insulation and variation in insulation thickness which affect the quality of the manufactured cables. The effect is that when rated current passes through these low-quality cables, it generates heat that these poor insulation cables cannot withstand. Therefore, it causes fire outbreaks commonly seen at the market places, homes and industries resulting in the loss of innocent lives and property almost every year [7].

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According to Narasimha and Rejikumar [8], the major root causes of these challenges or defects are due to the extrusion process parameters such as pressure, temperature, line speed, screw speed of the extrusion machine and properties of the raw material. Companies seek to minimize these defects through the use of controllers that monitor and control line speed, screw speed, pressure and temperature of the extrusion process. In this paper, consideration is given to effects caused by variation in the line speed of the electrical cable extrusion process.

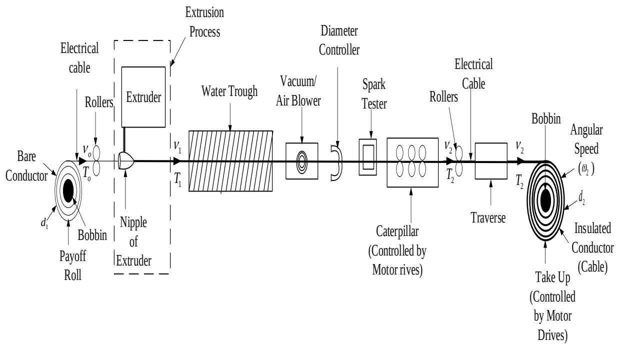


Figure 1. Functional diagram of an electrical cable extrusion line

Literature reviewed indicate that limited research has been conducted on temperature control of the cable extrusion process using conventional and intelligent techniques, but very little research has been done on the line speed control of the extrusion process. The control techniques employed include Proportional Integral Derivative (PID), Smith predictor PID, AWPI-PID, Fuzzy Logic, Finite Element Method (FEM) model and control, adaptive and multivariable control as reported in [9], [10], [11],[12], [13], [14], [15]. However, their limitations are unable to guarantee the maximum reduction in its settling time and overshoots.

Research has shown that ANFIS is easily implemented in many complex applications and can also handle huge data and find the best solution within the shortest possible time. However, the use of an ANFIS controller to control the line speed of the cable extrusion process to the best of authors' knowledge has not been reported in literature. Hence, this work aims to employ an ANFIS controller to achieve a better control response of the line speed during the cable extrusion process.

## *Line Speed Control of the Cable Extrusion Process*

The line speed of the extrusion process is the linear velocity of the cable in the extrusion line. It is the rate at which the extruded cable is being pulled by the haul-off and coiled by the take-up. The line speed is mainly controlled by the haul-off, pay-off and take-up drives and must be consistent to avoid cable defects. Therefore, the haul-off, pay-off and take-up drives must track the rotational speed of each other to keep the line speed constant to avoid variation in the required thickness of the extruded cable. Electrical cable extrusion lines are frequently run at exceptionally high speeds, so any errors such as insulation thickness can quickly escalate into extreme rejection rates. Effective speed control of the pay-off, haul-off and take-up drives are required during the extrusion process to ensure that cables of high quality are manufactured [16].

There are many types of motors and drives for extruder and downstream equipment used in cable extrusion lines. These motors include Direct Current (DC), AC induction and AC servo motors. The DC motors have some disadvantages such as sparking at brushes which could pose a danger of fire outbreak in industries associated with flammable products, and overheating due to overloads and incorrect voltages. It has a principal advantage of attaining a wide range of speed control with a variety of simple control methods. The speed of a DC motor is given by.

$$N\alpha \frac{E_b}{f} \text{Þ} N = K\frac{(V - I_a R)}{f} \tag{1}$$

From (1), the speed, N can be controlled by varying the flux per pole, (flux control method), varying the resistance in the armature circuit, R (armature control method), or varying the applied voltage, V (voltage control method) [17]. Increasing the flux and supply voltage increases the speed of the motor and subsequently the line speed and vice versa. Also, increasing the resistance decreases the speed of the motor and the line speed and vice versa.

AC induction motors have the advantages of simplicity and rugged construction, little maintenance, high efficiency, and self-starting torque. However, the induction motor has an inferior starting torque compared to DC shunt motors, energy loss associated with slip, which reduces the motor efficiency and has an almost constant speed, which cannot be easily changed. Despite the relatively constant speed operation of the induction motor, it has become the completely dominant electrical motor in many applications due to the advent of Variable Frequency Drives (VFDs). This enables the induction motor to be operated with more reliability, more efficiency and attain a wide range of speed control [18]. The induction motor speed is given by:

$$n = (1 - s)n_s \tag{2}$$

and the synchronous speed in terms of frequency is given by:

$$n_s = \frac{120 f}{p} \tag{3}$$

From (2) and (3) above, the speed of the induction motor can generally be varied by changing the frequency (f), the number of poles (p), slip (s), and supply voltage (V). Henceforth researchers have made attempts in controlling these speed parameters through the use of conventional and intelligent controllers.

### *Conventional Controllers*

Over 90% of the controllers in operation today are conventional controllers which include Proportional Integral Derivative (PID), Proportional (P), Proportional Integral (PI), and Proportional Derivative (PD) controllers [19]. These controllers offer the simplest and yet efficient solution to many real-world control problems. They have a basic structure and are easy to tune. In using these controllers mathematical modelling of the plant and tuning of controller parameters are required. The controller parameters include the proportional gain ($K_p$), integral gain ($K_i$)

and derivative gain ($K_d$). The standard form of the PID controller is shown in (4).

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (4)$$

Table 1 Formula for Ziegler-Nichols Tuning Method

| Controller Type | $K_p$ | $K_i$ | $K_d$ |
|---|---|---|---|
| P | $0.5K_{crit}$ | - | - |
| PI | $0.45K_{crit}$ | $1.2K_p/P_{cr}$ | - |
| PID | $0.6K_{crit}$ | $2K_p/P_{cr}$ | $K_p P_{cr}/8$ |

The proportional term provides an overall control action corresponding to the error signal. The integral term regulates steady-state errors and the derivative term regulates the transient response [20]. The Ziegler Nichols tuning method is the most common tuning method used in tuning of system parameters for conventional controllers. The formula for the Ziegler Nichols tuning method is illustrated in Table 1 [21].

### *Artificial Intelligence Techniques*

Artificial Intelligence (AI) techniques have vast applications in control systems. Past controllers made use of conventional controllers. Due to the overshoots and large settling time of these conventional controllers, their performance has become less satisfactory. However, intelligent controllers including Fuzzy Logic and Adaptive Neuro Fuzzy Inference System (ANFIS) are used to achieve high degrees performance.

*Fuzzy logic controller:* Fuzzy Logic Controller (FLC) is an intelligent technique that provides a means to deal with nonlinear functions using language and reasoning principles similar to how humans solve problems [22]. The reason behind development of FLC was because previous controllers require mathematical models of the plant that needed to be controlled. Inaccurate mathematical models of the plant will affect controller performance mostly for non-linear and complex control problems. FLC does not require mathematical models or expert knowledge of the plant. It is easier to implement fuzzy logic systems since they are based on natural language and human communication [23]. The FLC consists of four interfaces namely fuzzification, a rule base, an inference mechanism and defuzzification [23]. Despite the FLC's ability to control a plant without the need for a mathematical model, it is unable to learn and adjust to new environments.

*Adaptive neuro fuzzy inference system:* ANFIS is a multilayer network combination of ANN learning algorithms and Fuzzy Inference Systems (FISs) to map specific input parameters to an output. ANFIS uses the conventional interface and the learning capacity of ANN to enhance the systems' knowledge. The most used FIS model in ANFIS is the Takagi-Sugeno model since it is computationally efficient and works well with optimization and adaptive techniques [24].

Considering a FIS with two inputs x and y, output f and a feedforward network consisting of five layers, each layer comprises of either square nodes or circular nodes. The adaptive or square nodes consist of parameter sets that can be modified while the parameters of the fixed or circular nodes cannot be modified. The formula for the node functions may vary from layer to layer. A simplified architecture of the ANFIS is illustrated in Figure 2 [25].

The layer 1 ($O_i^1$) consists of input parameters of membership functions and the formula for its outcome is expressed in (5). The parameters in this layer are known as the premise parameters [26].

$$O_i^1 = \mu A_i(x), \ i = 1, 2 \quad (5)$$

Layer 2 ($O_i^2$) consists of the rule nodes where each node calculates the firing strength of the rule via multiplication. The formula for the firing angle and the total number of rules used in the structure are given in (6) and (7), respectively.

$$O_i^2 = \omega_i = \mu A_i(x) \times \mu B_i(y), \ i = 1, 2 \quad (6)$$

$$R_n = j^i \quad (7)$$

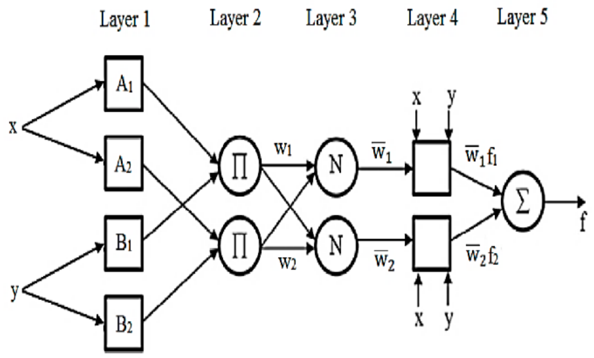


Figure. 2 ANFIS architecture

In layer 3 ($O_i^3$), each node computes the ratio of the i-th rule of the firing strength to the total of all the firing strengths. The nodes are referred to as average nodes and their outcome is shown in (8).

$$O_i^3 = \varpi_i = \frac{\omega_i}{\omega_1 + \omega_2}, \ i = 1, 2 \quad (8)$$

In layer 4, each node calculates the contribution of the i-th rule towards the overall output, and its outcome is expressed in (9).

$$O_i^4 = \varpi_i f_i = \varpi_i (p_i x + q_i y + r_i), \ i = 1, 2 \quad (9)$$

The final layer comprises the output node which sums the overall contribution of the layers and is expressed in (10).

$$O_i^5 = f = \sum_i \varpi_i f_i = \frac{\sum_i \omega_i f_i}{\sum_i \omega_i} \quad (10)$$


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The ANFIS architecture identifies variables by applying two learning algorithms, the backpropagation algorithm, and the hybrid learning algorithm. The learning algorithms compare the desired outputs to the measured system outputs and then the systems are tuned to narrow the difference between the two as much as possible.

## METHOD

Control of the extrusion line speed requires control of the pay-off, take-up and most importantly, the haul-off drives. The cable manufacturing company considered for this research is located in Ghana and uses both AC and DC drives in running their extrusion lines. These drives include a 1GG6206-0NF40-1WV3-Z Siemens DC motor in driving the pay-off which gradually unwinds the wire onto the extrusion line to be coated with insulation materials. G 11.0644 AEG DC motor for driving the haul-off which pulls the coated wire off the extrusion line and an IVE132S 3-phase AC servo motor and SVM-132-10 3-phase asynchronous servo motor for driving the take-up which winds the coated wire or cable onto reels.

These motors were controlled by obtaining an error speed computed by taking the difference between the reference speed and the actual speed of the drives at any instantaneous time. The error and change in error speeds were then passed through a designed controller. The output of the controller was compared to the drive current and then passed through a Pulse Width Modulation (PWM) circuit which converts the output into an equivalent signal to control the firing of the Insulated Gate Bipolar Transistor (IGBT) to finally control the drive speed. For the company considered for the research a typical cable size of 25 $mm^2$ has a recommended line speed of 63 m/min for XLPE and PVC insulation. Therefore, in this paper, the 25 $mm^2$ was considered as the load on the line and 63 m/min as the entire line speed to be controlled for PVC cable. Figure 3 illustrates the design concept of the proposed line speed control of an extrusion process. The pay-off drive was not considered because the size of the cable used in this work was small hence, will require minimum force to pull it. Therefore, the pulling for this cable size was done by the haul-off drive.

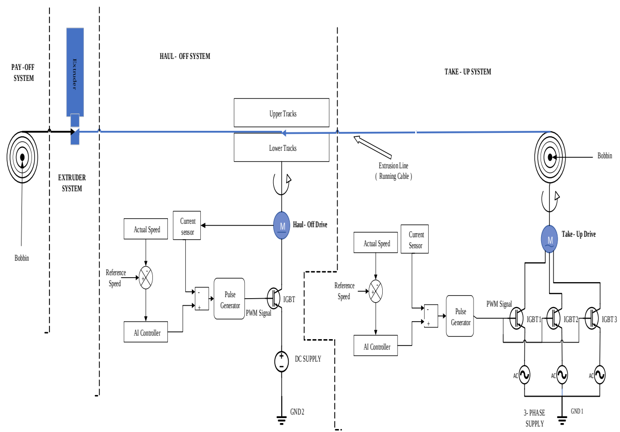
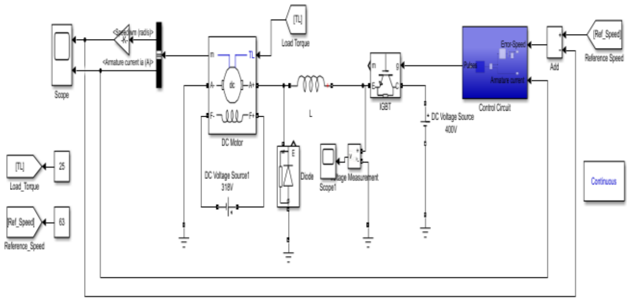


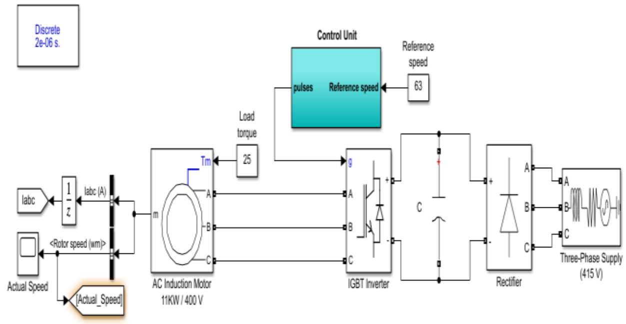

Figure 3 Design concept of the proposed speed control of an extrusion line.

### *Causes of Defects on Electrical Cables*

Data regarding the causes of defects during cable manufacturing for the month of February, 2020 were collected at the various extrusion lines at the cable manufacturing company considered for the research. The results are presented in Section 3.




(a) Haul-off system




(b) Take-up system

Figure 4. Simulink model of the main drives running an extrusion line

### *Modelling of the line speed of the cable extrusion process*

The line speed for the extrusion system consisting of the haul-off DC motor and the take-up AC servo motor as the principal drives were modelled using the MATLAB/Simulink blocks of the drives that run the extrusion line as shown in Figure. 4. The process parameters were obtained from the nameplates of the speed drives. The haul-off DC motor and the take-up AC servo motor were modelled separately but given the same setpoint speed of 63 m/mins as the extrusion line speed and the same load torque of 25 Nm as the load of the entire extrusion line. This is because when the speed of the take-up drive drops due to the accumulation of weight on the bobbin as a result of the winding of cable unto the bobbin, the controller must ensure that more current is supplied to the take-up motor so as to increase the torque and bring the motor to the required or setpoint speed so as to maintain a constant line speed.

### *Modelling of the Haul-Off and the Take-Up Drives*

The model of the haul-off and take-up drives both consist of the reference speed as the setpoint speed, Insulated Gate Bipolar Transistor (IGBT) as the converter circuit which regulates the supply voltage supplied to the respective motors. The model also consists of a control circuit block containing the main controller and pulse generator which generate the required gate pulse for the IGBT to regulate the supplied voltage to the respective motors in Figure 4. The reference speed used for the various controllers is 63 m/min for cable size of 25 $mm^2$.

### *Design of PID Controller*

The Ziegler Nichols tuning method was used in tuning the $K_p$, $K_i$, and $K_d$ values to ensure efficient response of the PID controller. The PID control parameters were tuned by maintaining the $K_i$ and $K_d$ gain values at zero and increasing the $K_p$ value from zero to a critical gain, $K_{crit}$ at which sustained oscillations of the system occur. The critical gain was obtained as 40.00 and 90.00 and the corresponding period known as the critical period ($P_{cri}$) was obtained as 0.82187 second and 0.333 second for the take-up and haul-off respectively. From the Ziegler Nichols tuning method shown in Table 1, the $K_p$, $K_i$ and $K_d$ values were obtained as 24.00, 58.4035, 2.4656 respectively for the take-up and 54.00, 324.324, 2.2275 respectively for the haul-off. The sustained oscillations and the Simulink model of the conventional PID controller with the take-up system and the haul-off system of the extrusion line is shown in Figure 5 and Figure 6 respectively.

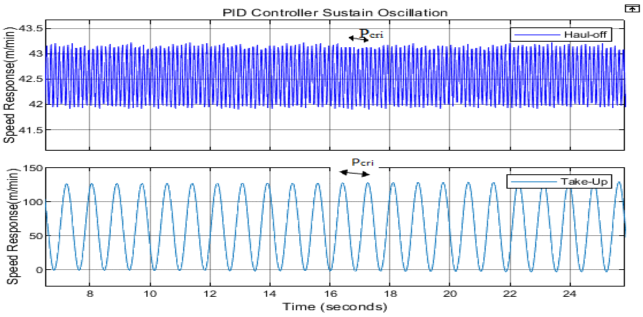
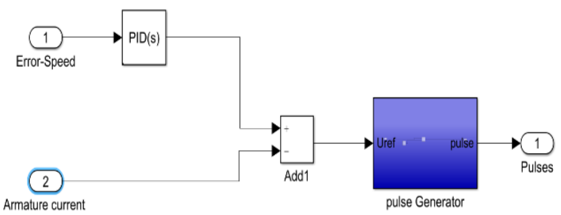
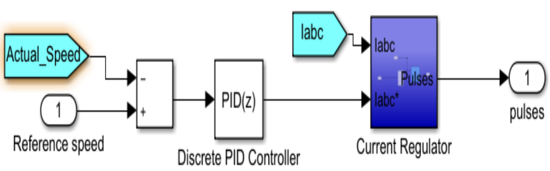



Figure. 5 Sustained oscillations of PID controller



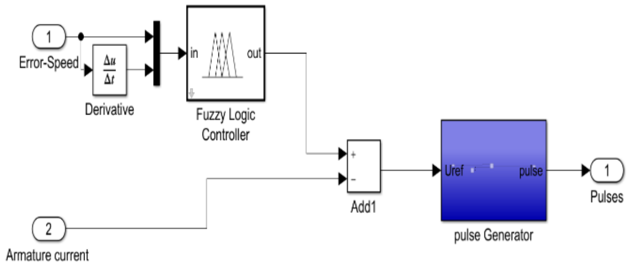

(a) Haul-off PID



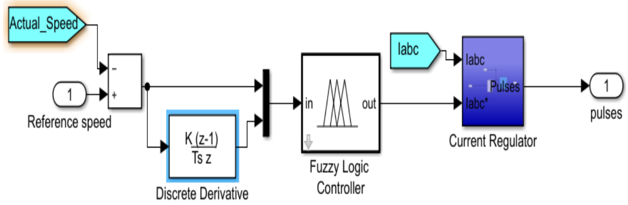

(b) Take-up PID controller
Figure. 6 Simulink model of PID controller

### *Design of Fuzzy Logic Controller*

The advent of FLC technique has helped to replicate the human thinking process in its control algorithm. The FLC was used in order to achieve a stable, precise, and reliable performance of the extrusion line speed. The FLC takes two inputs, error e(t) and change in error ė(t) and gives one output u(t) representing the control signal. The Simulink model of FLC is shown in Figure. 7.

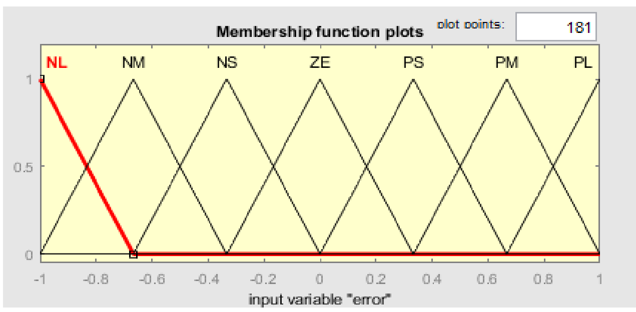



(a) Haul-off fuzzy logic controller

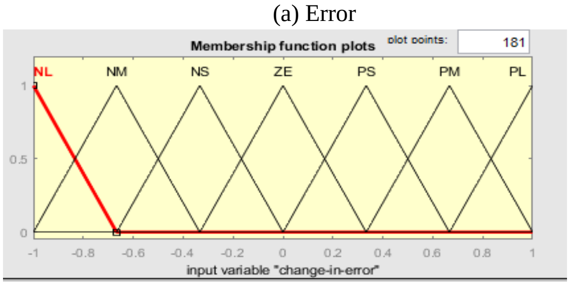



(b) Take-up fuzzy logic controller
Fig. 7 Simulink Model of Fuzzy Logic controller

Fuzzification: The fuzzification involves converting from crisp values to fuzzy values. The triangular membership functions were used to fuzzify the inputs in this work due to reduction in its steady-state error, simplicity and computational efficiency compared to trapezoidal, Gaussian and bell-shaped membership functions [27]. Seven triangular membership functions were used for the inputs and the output variable as shown in Figure. 8 and Figure 9, respectively. The range of membership functions of the error e(t), change in error ė(t) and output u(t) is [-1 1] and was specified based on the tolerance of the haul-off and take-up system.




(a) Error




(b) Change in error
Figure. 8 Input membership functions of the fuzzy logic controller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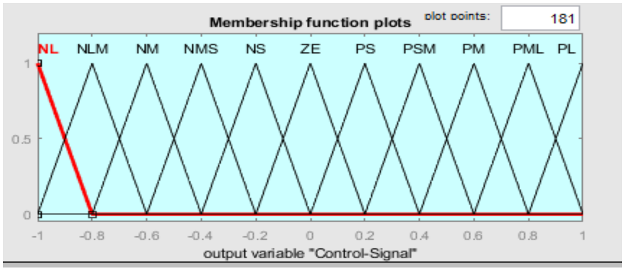



Figure. 9 Output Membership Functions of the Fuzzy Logic Controller

*Fuzzy rule base:* The rules used for the design of the FLC are given in Table 2. The controller uses seven variables for the error e(t), change in error ė(t) and the output u(t) signal with 49 rules as the rule base. The if-then format was used in defining the 49 rules. The linguistic variables were defined as NL = Negative Large, NM = Negative Medium, NS = Negative Small, ZE = Zero, PS = Positive Small, PM = Positive Medium and PL = Positive Large for the inputs and NL = Negative Large, NLM = Negative Large Medium, NM = Negative Medium, NMS = Negative Medium Small, NS = Negative Small, ZE = Zero, PS = Positive Small, PMS = Positive Medium Small, PM = Positive Medium, PML = Positive Medium Large and PL = Positive Large for the output.

The rules are stated such that if the speed error e(t) is NS and change in error ė(t) is NS, there will be an increase in speed hence the output should be NMS to allow speed reduction.

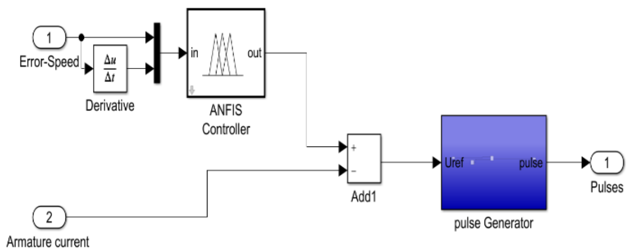
Table 2 Fuzzy Base Rules [28]

| e(t)/ė(t) | NL | NM | NS | ZE | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NL | NL | NL | NLM | NM | NMS | NS | ZE |
| NM | NL | NLM | NM | NMS | NS | ZE | PS |
| NS | NLM | NM | NMS | NS | ZE | PS | PMS |
| ZE | NM | NMS | NS | ZE | PS | PMS | PM |
| PS | NMS | NS | ZE | PS | PMS | PM | PLM |
| PM | NS | ZE | PS | PMS | PM | PLM | PL |
| PL | ZE | PS | PMS | PM | PLM | PL | PL |

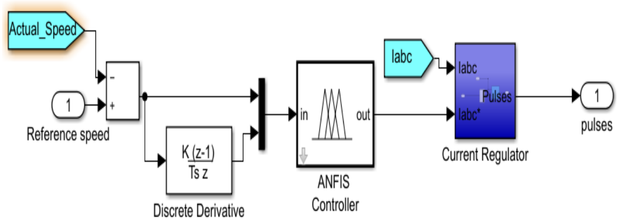
*Defuzzification of the output:* The defuzzification process converts the fuzzy output which is the control signal into a crisp value to control the plant. The centroid method of defuzzification was used to obtain the crisp value due to its computational efficiency.

### *Design of the ANFIS Controller*

The ANFIS combines the advantages of both ANN and Fuzzy Logic (FL) system. The ANN provides learning abilities and the FL provides a fuzzy if-then rule of thinking and reasoning to the system [29]. The ANFIS controller has self-learning, organizing and tuning abilities, hence it does not require a manual generation of rules and membership functions. Figure 10 shows the MATLAB/Simulink model of the ANFIS controller with a reference speed of 63 m/min.

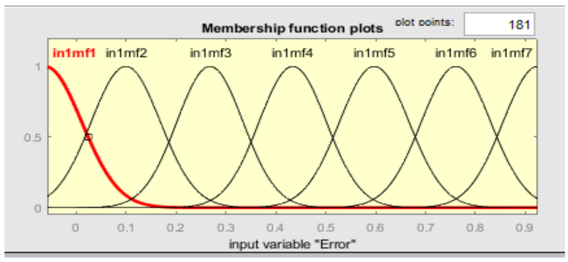



(a) Haul-off ANFIS controller

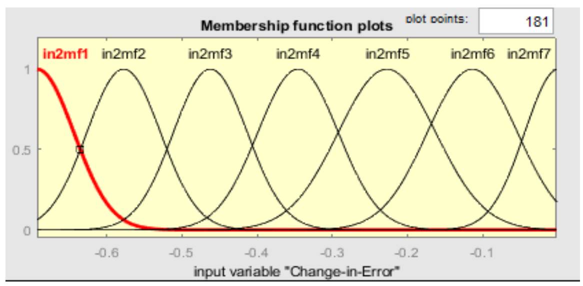



(b) Take-up ANFIS controller
Figure. 10 Simulink model of ANFIS controller

The model uses two inputs, error e(t) and change in error ė(t) and a single output u(t) is given as the control signal. The model also uses the Takagi-Sugeno (TS) model for its fuzzy structure due to its efficiency and compatibility with adaptive techniques and optimization. The model also employed the Gaussian membership function due to its less training error compared to other membership functions. Figure 11 shows the membership functions of the ANFIS controller. The ANN trains the data given to it and automatically generates rules using the fuzzy if-then format, range of input membership functions and assigns values to the output.




(a) Error




(b) Change in error
Figure 11 Input membership functions of the ANFIS controller

The error e(t), change in error ė(t) and its corresponding output u(t) were obtained by running the model with the FLC and were randomly sampled. Figure. 12 shows the training and testing data of the ANFIS. The red dots represent testing data while the blue circle sign represents the training data. The data obtained from the extrusion line system were trained using the ANFIS controller editor block in MATLAB and its Mean Squared Error (MSE) or training error was obtained as illustrated in Figure 13. The editor block uses an epoch of 100 and an error tolerance of zero in training the data. The ANFIS output was tested with the same data used for the training.

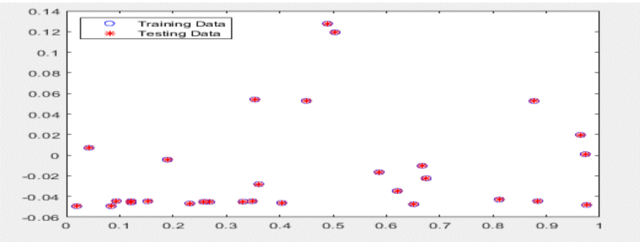



Figure. 12 Training and testing data for the ANFIS editor block

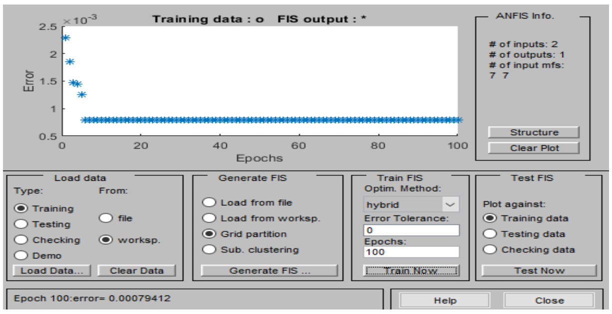



Figure. 13 Mean square error for ANFIS controller

## RESULTS AND DISCUSSION

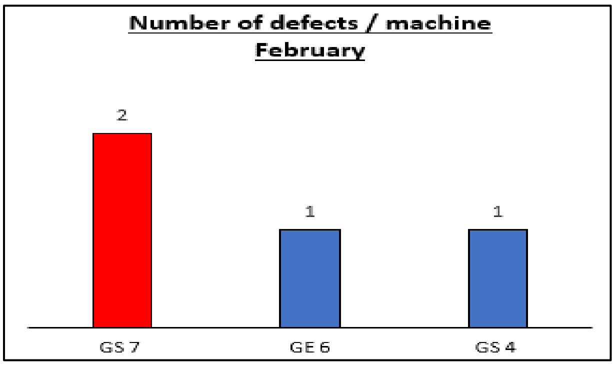
### *Results from the Analysis of the Causes of Defects on Electrical Cables*

The analysis of the causes of cable defects are shown in Figure 14, Figure 15 and Figure 16, respectively. The analysis indicated that the break in insulation/sheath which occurred 2 times was the frequently occurred defect during the cable manufacturing process. The GS 7 line with 2 defects had the highest number of defects among the extrusion lines, 75% of the defects were recorded during the morning shift, and the machines such as the haul-off and take-up used in the cable manufacturing process contribute to 50% of the defects in the cable being manufactured due to the inability of these machines in keeping the line speed constant, hence the high number of breaks in insulation/sheath defect. Other causes of defects include the environment in which the extrusion process was carried out and the people working in the extrusion line.

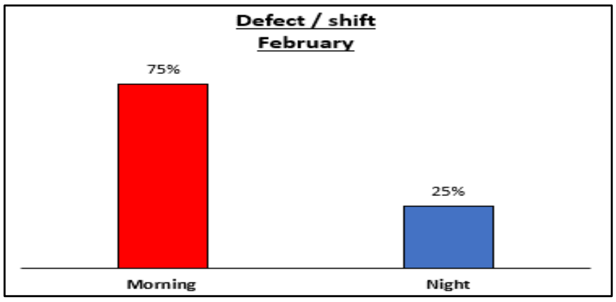
### *Results from Controllers*

*PID Controller Response*

The system was given a reference speed of 63 m/min and uses a MATLAB/Simulink in-build DC motor block for the haul-off system and an AC induction motor block for the take-up system. Figure. 17 shows the MATLAB/Simulink results of the system with PID controller. The system's performance with the PID controller shows that the speed oscillates with high overshoots for both haul-off and take-up systems and takes more time to settle. This indicates an oscillation with high overshoots and large settling time for the entire extrusion line.

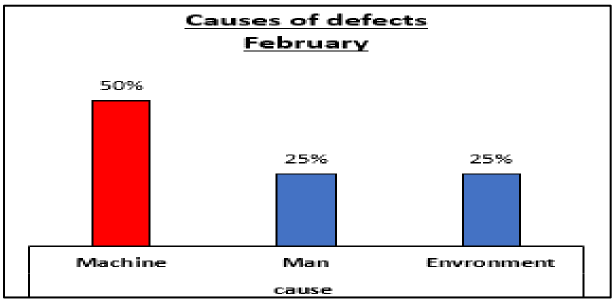



(a) Number of defects/machine

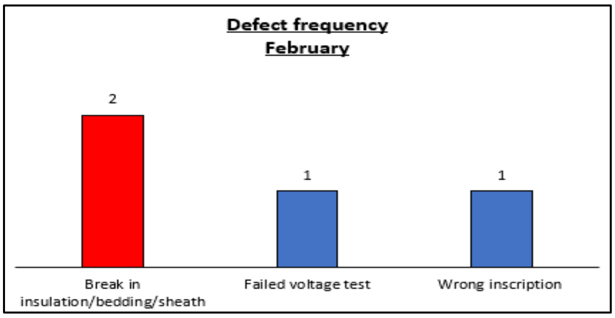



(b) Defects/shift

Figure. 14 Number of Defects and Shift




(a) Causes of defects




(b) Defects frequency

Figure. 15 Causes of cable defects and defect frequency

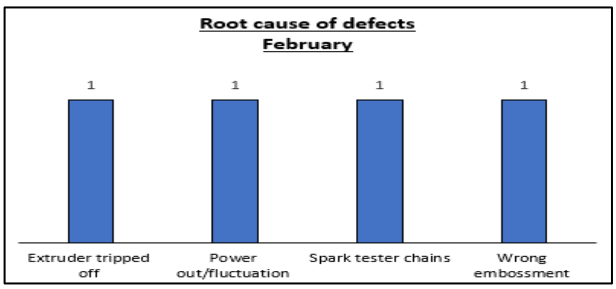



Figure 16 Root cause of defects


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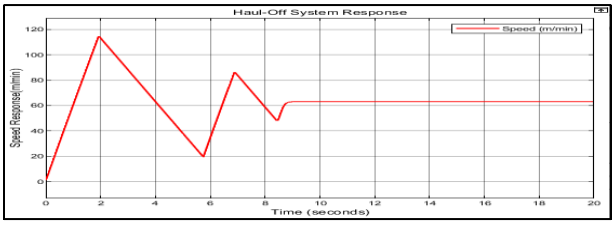
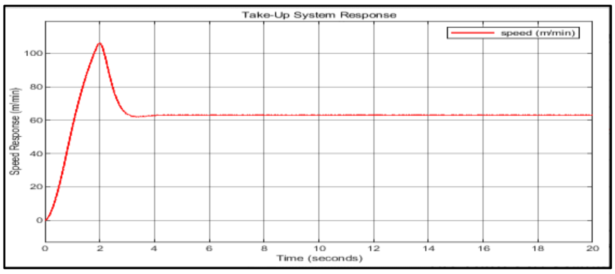
Table 3 Performance specification of controllers.

| | | Haul-Off Controller Response | | | Take-Up Controller Response | | |
|---|---|---|---|---|---|---|---|
| **SN** | **Controller** | **Rise Time (s)** | **Settling Time (s)** | **Overshoot (%)** | **Rise Time (s)** | **Settling Time (s)** | **Overshoot (%)** |
| **1** | PID | 0.216 | 71.552 | 8.800 | 0.7530 | 68.644 | 4.400 |
| **2** | Fuzzy Logic | 3.340 | 0.501 | 7.414 | 2.831 | 0.505 | 7.800 |
| **3** | ANFIS | 1.717 | 0.000 | 4.100 | 3.083 | 0.000 | 6.050 |




(a) Haul-off responses

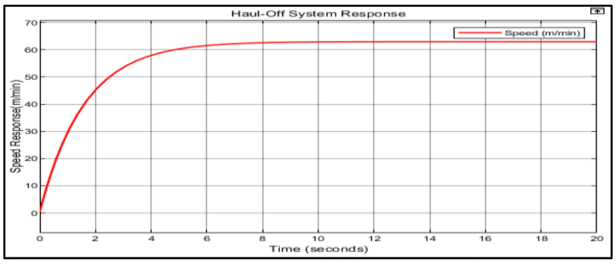



(b) Take-up system response

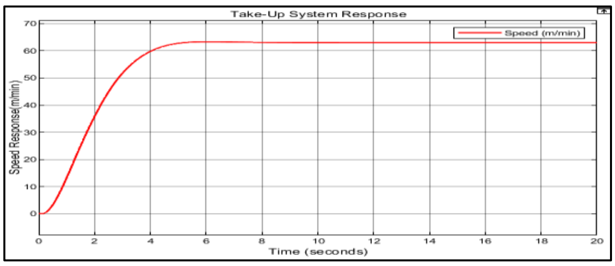
Figure. 17 PID controller response

### *Fuzzy Logic Controller Response*

The FLC produces a smaller percentage of overshoot, settles faster and it is more stable as compared to the PID controller.




(a) Haul-off system

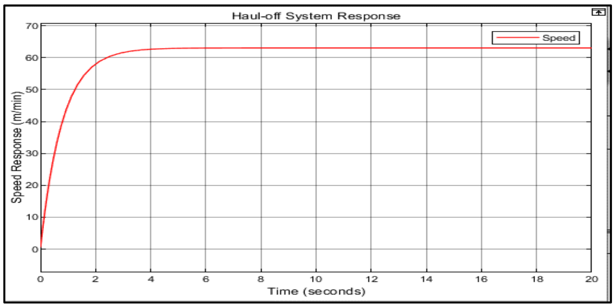



(b) Take-up system response

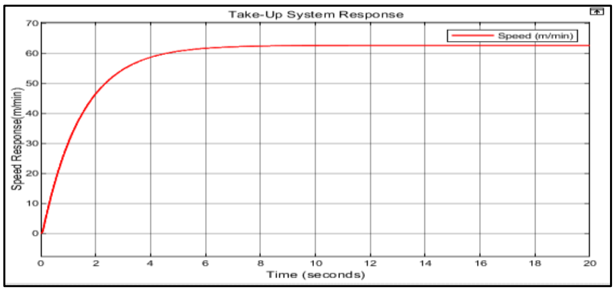
Fig. 18 Fuzzy Controller Response

### *ANFIS Controller Response*

The response of the system for the ANFIS controller in MATLAB/Simulink is shown in Figure 19. The results of the ANFIS controller show better performance of the system as compared to the PID and fuzzy controllers in terms of percentage overshoot, settling time, reference speed tracking and steady-state response.




(a) Haul-off system




(b) Take-up system response

Figure. 19 ANFIS controller response

The combined response and the performance specification for all the controllers are shown in Table 3.

### ***Discussion***

From Figure. 14, Figure. 15 and Figure. 16, it can be seen that the GS 7 line caused 2 defects making it the line that causes more defects among the three lines as illustrated in Table 3. 1, and the morning shift also generated 75% of the defects due to the fact that more of the extrusion work is carried out during the morning shift. Break in insulation was found to be the frequently occurred defect and the machines such as the haul-off and take-up used in the extrusion process generated 50% of the total defects. The root causes of the defects were equal between extruder tripped off, power out/fluctuation, spark tester chains, and wrong embossment. This implies that the machines used for the cable manufacturing process must be adequately controlled especially the haul-off and take-up systems.

In Figure 17, Figure 18, Figure 19 and Table 3, it can be observed that the PID controller gave a peak overshoot of 71.552%, and 68.644%, a settling time of 8.8 seconds and 9.82 seconds for the haul-off and take-up, respectively. Hence, the PID controller becomes less efficient for use due to its high overshoots and settling time for both haul-off and take-up drives, respectively. The FLC compensates for these challenges by reducing overshoots to 0.468% and 0.505%, a settling time of 7.414 seconds and 7.80 seconds for the haul-off and take-up respectively. The system response characteristics were further improved using the ANFIS controller, which was able to produce a settling time of 4.100 seconds and 6.05 seconds, a percentage overshoot of 0% for the haul-off and take-up, respectively. The ANFIS controller was robust in maintaining stability and controlling the system's output as compared to the conventional PID and FLC.

## CONCLUSIONS

In conclusion, the design of an ANFIS line speed controller has been achieved. Based on the results obtained from the simulations of the conventional PID, FL and ANFIS controllers, the ANFIS controller demonstrated better performance than the other controllers when subjected to the same operating conditions. The ANFIS controller, therefore, helped maintain the line speed of the extrusion process constant and has faster response under the same conditions compared to the conventional PID and FLC. It is therefore recommended that a prototype of the ANFIS line speed controller should be considered in controlling the line speed of the extrusion process in the cable manufacturing industries to ensure a constant line speed during cable extrusion processes so as to produce quality products, stay competitive and also, minimize the production of scraps. Also, optimization techniques such as Bacterial Foraging Algorithm (BFA), Particle Swarm Optimization (PSO), Ant Colony Optimization Algorithm (ACOA), and Firefly Algorithm (FA) among others should be considered to optimize the ANFIS controller to further improve its performance to effectively control the line speed of the extrusion process.

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## NOMENCLATURE

| | |
|---|---|
| $\phi$ | Flux per pole |
| $\omega_i$ | Firing strength |
| $E_b$ | Back emf |
| $N$ | Speed of rotation |
| $\phi$ | Flux per pole |
| $K$ | Constant |
| $I_a$ | Armature current |
| $R_a$ | shunt-wound motor\ |
| $R_a + R_{se}$ | for series and compound wound motors |
| n | rotor speed |
| s | slip |
| f | supply frequency |
| p | number of poles. |
| u(t) | controller output |
| e(t) | error signal |
| $A_i$ | membership function associated with the node |
| x, y | inputs to the structure |
| $A_i$, $B_i$ | membership function associated with the node |
| $\omega_i$ | firing strength |
| $R_n$ | total number of rules |
| i | number of inputs |
| $j$ | number of membership functions per input |
| $p_i$, $q_i$ and $r_i$ | consequent parameters |
| $f_i$ | = algebraic function of consequent parameters |

## AUTHOR(S) BIOGRAPHY

**Robert Agyare Ofosu** is a Lecturer in the Electrical and Electronic Engineering Department at the University of Mines and Technology (UMaT), Tarkwa, Ghana. He holds the degrees of BSc Electrical and Electronic Engineering from UMaT and MSc Electrical and Electronic Engineering (Control Engineering Option) from Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya and currently pursuing his PhD in Jiangsu University, China. He is a member of the Institute of Electrical and Electronic Engineers (IEEE). His research interests include control engineering, industrial automation, embedded systems, electrical machines and drives and artificial intelligence.

**Ewin Normanyo** is a Senior Lecturer in the Electrical and Electronic Engineering Department at the University of Mines and Technology, Tarkwa, Ghana. He holds MSc degree in Electromechanical Engineering from the Kharkov State University, Ukraine. He is a member of the Ghana Institution of Engineers. His research interests include industrial automation, industrial energy management, instrumentation systems, control engineering, automated electric drives and mechatronics.

**N-Yo. Abdul-Aziz** is a graduate of the University of Mines and Technology, Tarkwa, Ghana. He holds a Bachelor of Science degree in Electrical and Electronic Engineering. His research interests include Control Systems, Power Systems and Engineering management.

**Stephen Smart Stickings** is the Quality Control Manager of Nexans Kabelmetal Ghana limited, Tema He holds a Bachelor of Science degree in Electrical and Electronic Engineering. He is a member of the Ghana Institution of Engineers (GhIE). His area of interests includes control engineering and cable manufacturing technology.

## APPENDICES

### *APPENDIX A*

*The Specifications of The Various Drives for The Extrusion Line*

**Table A1 Specifications of the Haul-Off Drive**

| Parameter | Specifications |
|---|---|
| Type of Motor | DC Motor |
| Armature voltage | 400 V |
| Armature current | 40.7 A |
| Field voltage | 318 V |
| Field current | 1.38 A |
| Motor speed | 20 – 3120 RPM |
| Power rating | 14.3 KW |
| Armature Resistance | 9.828 Ohms |
| Field Resistance | 230.435 Ohms |

**Table A2 Specifications of the Take-Up drive**

| Parameter | Specifications |
|---|---|
| Type of Motor | 3 Phase AC Servo Motor |
| Supply frequency | 50 Hz |
| Voltage (star connected) | 380V |
| Current | 21.36 A |
| Power | 11 KW |
| Maximum speed | 6000 RPM |
| Resistance | 0.38 Ohms |
| Inductance | 4.85 mH |
| Nominal speed | 1000 RPM |
| Phase voltage | 220V |


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