Fuzzy-Neural Control of Hot-Rolling Mill

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ABSTRACT:

This paper deals with the application of Fuzzy-Neural Networks (FNNs) in multi-machine system control applied on hot steel rolling. The electrical drives that used in rolling system are a set of three-phase induction motors (IM) controlled by indirect field-oriented control (IFO). The fundamental goal of this type of control is to eliminate the coupling influence though the coordinate transformation in order to make the AC motor behaves like a separately excited DC motor. Then use Fuzzy-Neural Network in control the IM speed and the rolling plant. In this work MATLAB/SIMULINK models are proposed and implemented for the entire structures. Simulation results are presented to verify the effectiveness of the proposed control schemes. It is found that the proposed system is robust in that it eliminates the disturbances considerably.

I. Introduction

Over the past few years, the rolling mills and processing industries have seen significant production capacity increases. This level of growth is expected to continue going forward, but will not necessarily in new plants [1]. Interconnections of different machines in such a way that they maintain the synchronization among them are called multi-machine systems, as in rolling mills. Rolling processes have entered in various applications, such as paper, textile, aluminum, and steel productions. T. Matinetz, P. Protzel, and O. Gramckow, in 1994 [2], gave a brief survey of the different control aspects with Neural Network. Alaa Muhideen and A. A. Ali, 2002 investigated steel rolling using DC motors and Neural Network [3]. Lipo Wang, and Yakov Frayman, in 2002, used a dynamically generated Fuzzy-Neural-Network (FNN) controller applied to a real-world application of controlling the torsional vibration of tandem cold-rolling mill spindles with a simulated plant [4].

Arno Barry Samuel Ferreira, (2005) [5], had designed and controlled a system of automatically steering a stainless steel strip passing through a steel mill, by adjusting the level or parallelism of the rolls.

Two types of steel rolling exist - hot rolling and cold rolling. In hot rolling mill the iron is kept in the blast furnace to reach temperatures over 1000 ^{o}C. The iron comes out as slabs of fixed length and cross-section called billets, to be sent to the rolling stands for forming [6].

II. The Process of Hot Rolling Mills

In the hot strip mill, the slab is reheated in the furnace. In order to obtain the desired metallurgical properties and dimensions, the slab undergoes various stages in the reheating furnace after which it is delivered to the roughing and the finishing mills. In the hot rolling process, the slab dimensions are transferred to target values and the austenite gain size is altered. The strip is cooled down and wrapped to a coil shape. The mechanical properties are then determined at the cooling stage [7,8].

Hot rolling is the process of shaping the steel, aluminum, or any other metal into an elongated element with a specified constant cross-section. Simple shapes include round rods and flat bars, plates, strips, and sheets, while complex shapes include shapes of I, H, T, L, U, C, and Z shapes [9]. The line production consists of several rolling stands. Every rolling stand contains two to four rolls driven by an induction motor.

To avoid drooping of the production heads, shears are used to cut the drooping heads. Two shears are utilized in the system, one at the middle of the line and the other at end of the line for end cropping. As shown in Fig. (1), loops are formed at the finishing group to increase quality of the production by reducing the tension applied on the line. Therefore, speed regulation is necessary to ensure constant tension on the line.

Figure (2) shows the finishing mill. At the finishing mill with its horizontal rolls only the thickness of the strip can be controlled, not its width. The width is determined in a rolling process with vertical rolls, which is performed before the strip runs into the finishing mill. The problem, however, is that during the horizontal rolling the width of the strip does change. To obtain the desired width at the end of the rolling process, it is necessary to estimate the widening of the strip by the horizontal rolling. A good estimate for this widening then enables one to reduce the width of the strip by this amount with the vertical rolling, which then leads to the required final width of the strip after the whole rolling process [2].

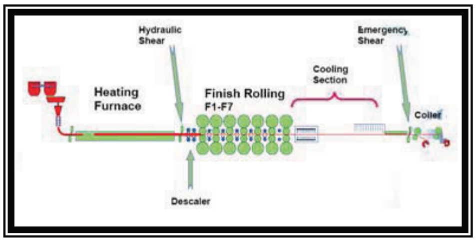

Fig. (1) Product Line Planform.

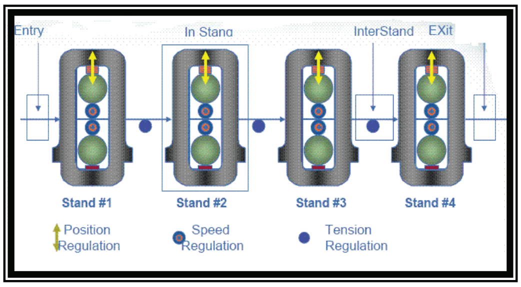

Fig. (2) Sketch of a hot wide strip mill consisting of four stands.

Rolling speed is one of the most important variables in the steel- and aluminum-making processes. At high rolling speed, the strain of the material and rolling load are increased, which improves the contact between the sample and the roll. The rolling speed for the hot working of the sample also affects the properties of the metal. For instance, higher rolling speed increases the work hardening and strain rate, therefore, higher strength metal are produced. Increasing rolling speed can also reduce the contact time of metal and hence reducing the heat loss during the process. On the other hand, the slower the speed in the mill, the higher is the permissible reduction without the danger of damaging the metal surface [10].

III. Loop control and synchronization;

When the length of the production line is greater than the distance between subsequent stands, the loops are formed. These loops may be either up loops or down loops. Loops are formed when tension is not at the desired value, and due to this when rolling conditions change tension may cause to tighten the production and reduces its quality [4]. Loppers are put to work when head of the line production starts to enter the next (downstream) stand, and they are released when tail of the line production exist from the upstream stand. Photo sensors are put behind and at the front of every stand involve loops, which sense the existence of the line.

In rolling systems, speed synchronization between different stands is very important to avoid system breakdown, which is very serious matter in rolling systems. This process can be achieved by keeping the flow rate of the metal fixed from first stand, which is the metal source, to the last one (train governor). Subsequently, the flow rate of the metal must be constant between every successive stands. Flow rate equation of M-stands is [11]:

$$S_1.v_1=S_2.v_2= . . = S_M v_M \qquad \ldots\ldots \quad (1)$$

Wherein any change in the speed (v) of a stand must followed by a change in the metal volume (S) from its upstream stand till first stand. This will cause a change in the loop length and subsequently the loop height. The controller has to adjust the drive speed in order to keep the loop height in the required set point.

In real system, the distance between successive stands is about D=5 m, and loop height (h) is 0.3 m, so the loop length (d) can be approximated using a triangular relation described by [11]:

$$d = 2\sqrt{(\frac{D}{2})^2 + h^2} \qquad \ldots\ldots \quad (2)$$

Knowing D and the height reference hr_i, then one can obtain time of span Tr_i to leave the line stand (i) and reaches stand (i+1) using:

$$Tr_i = \frac{1}{v_i}\sqrt{D^2 + (2.hr_i)^2} \qquad \ldots\ldots \quad (3)$$

Then, the instantaneous time equation of the loop length is:

$$d_i = Tr_i . v_i(t) \quad \ldots\ldots \ (4)$$

As shown from Fig. (3) the loop lengths are affected by speeds of both stands where the loop is built, and using eqn. (1) one can find the final formula for the loop length $d_i(t)$ and its corresponding height $h_i(t)$ using :

$$d_i(t) = Tr_i.(v_i(t) - \frac{v_{i+1}(t)}{\mu_i}) + dr_i \quad \ldots \ (5)$$

$$h_i(t) = \frac{1}{2}\sqrt{d_i^{\,2}(t) - D^2} \quad \ldots\ldots \ (6)$$

where v_i = linear velocity of the (ith) stand,
R = Rolling diameter,
μ_i = Reduction factor of the (ith) stand.

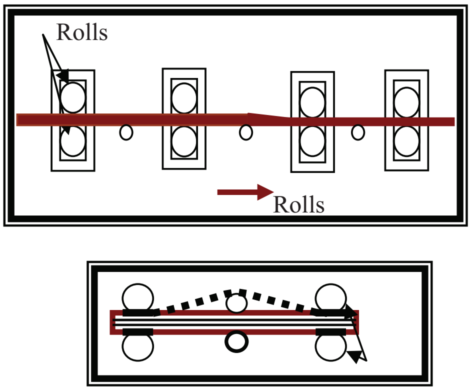

Fig (3) Steel rolling system.

The PI controller is sufficient to insure that the loop height tracks its reference. Free rolling is obtained when linear velocity $v_i(t)$ of stand i equals to $v_{i+1}(t)/\mu_i$ and so that $h_i(t)$ will track hr_i block diagram representation of the rolling system including the loop controllers is shown in Fig. (4). The system has M rolling stands, each stand consists of an Induction Motor (IM) drive and its controller. In Fig (4), the block denoted by C_i represents the equations (2) to (6).

As observed from Fig. (4), the stand M contains no loop controller because it is the speed governor of the rolling train. The linear speed error ($v_i(t)$-$v_{i+1}(t)/\mu_i$) will be converted by C(i) to the corresponding height. This height will be corrected by the loop controller M-1 to track its height reference hr_{M-1} the same procedure will be devoted for the rest of the loop controllers till first stand. The loop controller is a conventional PI-controller and for every stand speed controller is PI-based Indirect Field Oriented Controller (PI-IFOC).

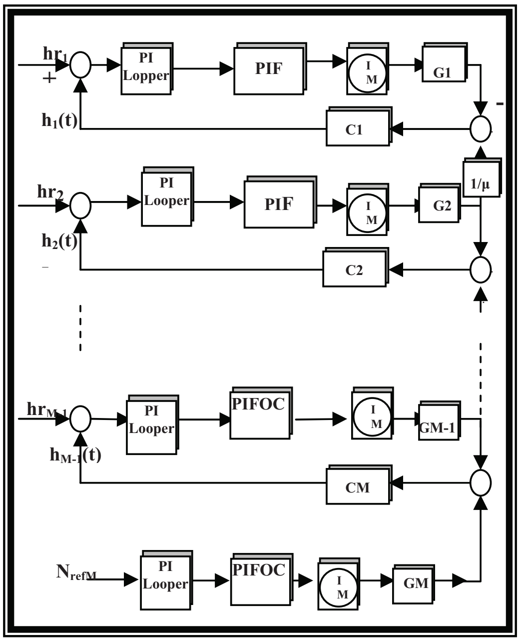

Fig. (4) Rolling system with only PI control

According to the developments in robustness controllers, they promised for obtaining better outcomes by implementing Fuzzy-Neural Networks as controllers instead of the conventional type in the rolling system applications.

IV. Indirect Field Oriented Control (IFOC):

The rotor circuit equation of the IM can be written as [12,13]:

$$\frac{d\lambda_{dr}}{dt} + R_r i_{dr} - (\omega - \omega_r)\lambda_{qr} = 0 \quad ..(7)$$

$$\frac{d\lambda_{qr}}{dt} + R_r i_{qr} - (\omega - \omega_r)\lambda_{dr} = 0 \quad ...(8)$$

The rotor flux linkage expressions can be written as :

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad \ldots\ldots.(9)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad \ldots.(10)$$

The rotor currents can be written from (9) and (10) as:

$$i_{dr} = \frac{1}{L_r}\lambda_{dr} - \frac{L_m}{L_r} i_{ds} \quad \ldots..(11)$$

$$i_{qr} = \frac{1}{L_r}\lambda_{qr} - \frac{L_m}{L_r} i_{qs} \quad \ldots.(12)$$

Substituting the rotor equations (11) and (12) into (7) and (8), they become:

$$\frac{d\lambda_{dr}}{dt}+\frac{R_r}{L_r}\lambda_{dr}-\frac{L_m}{L_r}R_r i_{ds}-\omega_{sl}\lambda_{qr}=0 \qquad \ldots(13)$$

$$\frac{d\lambda_{qr}}{dt}+\frac{R_r}{L_r}\lambda_{qr}-\frac{L_m}{L_r}R_r i_{qs}-\omega_{sl}\lambda_{dr}=0 \qquad \ldots(14)$$

where, R : is a resistance term,

L : is self inductance term for each coil.

i : is the instantaneous current.
L_m is the mutual inductance the machine.
Parameters are subscripted by (d) for direct axis variables and (q) for quadrature axis variables and

$\omega_{sl} = \omega - \omega_r$
For decoupling control, it is desirable that:

$$\lambda_{qr}=0 \qquad \ldots.(15)$$

This implies,

$$\frac{d\lambda_{dr}}{dt}=0 \qquad \ldots(16)$$

So that the total rotor flux λ_r is directed along the d-axis.

Substituting the above conditions in equations (13) and (14), we get

$$\frac{L_r}{R_r}\frac{d\lambda_r}{dt}+\lambda_r=L_m i_{ds} \qquad \ldots.(17)$$

$$\omega_{sl}=\frac{L_m}{\lambda_r}\frac{R_r}{L_r}i_{qs} \qquad \ldots.(18)$$

where: $\lambda_r=\lambda_{dr}$ has been substituted.

If rotor flux λ_r = constant, then from Eq. (17)

$$\lambda_r=L_m i_{ds} \qquad \ldots.(19)$$

Then the slip signal (ω_{sl}) can be written as:

$$\omega_{sl}=\frac{1}{\tau_r}\frac{i_{qs}}{i_{ds}} \qquad \ldots..(20)$$

Where $\tau_r = L_r/R_r$ (time cons.)

The torque developed by the induction motor is given by:

$$T_e=\frac{3}{2}\frac{P}{2}(\lambda_{dr}i_{qr}-\lambda_{qr}i_{dr}) \qquad ..(21)$$

Because of decoupled control, from (14), (20) can be written as follows:

$$T_e=\frac{3}{2}\frac{P}{2}(\lambda_{dr}\,i_{qr}) \qquad \ldots(22)$$

Using (12) to replace i_{qr} in (22), it follows:

$$T_e=\frac{3}{2}\frac{P}{2}\lambda_{dr}\left(\frac{1}{L_r}\lambda_{qr}-\frac{L_m}{L_r}i_{qs}\right) \qquad ..(23)$$

$$T_e=\frac{3P}{4}\frac{L_m}{L_r}\lambda_{dr}\,i_{qs} \qquad \ldots(24)$$

An alternative to the direct sensing of flux position is to employ the slip relation, given in equation (19), to estimate the flux position. Figure (5) illustrates this concept and shows how the rotor flux position can be obtained by integrating the sum of the rotor speed and the command slip frequency calculated using equation (20). In the steady state this corresponds to setting the slip to the specific value which divides the stator current into flux producing and torque producing components. Indirect field orientation does not have inherent low speed problems and is thus preferred in most systems which must operate near zero speed.

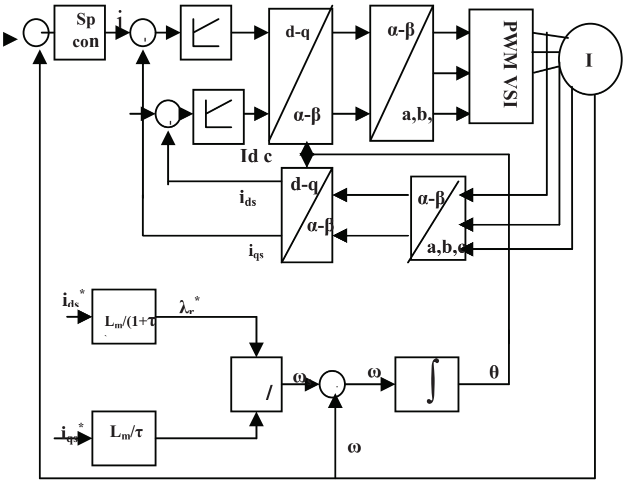

Fig. (5) Indirect Field Oriented drive system

V. Fully-Fuzzy-Neural Network Scheme

Several benefits have been obtained from the semi-fuzzy-neural scheme structures, which are reduced effect of the perturbations when a direct FN is employed for the induction motor speed controller in the conventional fuzzy neural structure, and the immediate cancellation of the changes by using a FN for the loop height controller in fuzzy neural conventional structure [11]. These utilities light the way for combining both FN of the induction motor field oriented controller and of the loop controller and the constructing a fully-fuzzy-neural scheme.

The Fuzzy-Neural identifier employed in one motor structure has been used with this scheme for the sake of comparison. These networks are indirect controller for the induction motor speed control and the direct controller for the loop height controller. Both of them will have the same network characteristics mentioned lately.

A path is required to propagate the height error to the fuzzy neural loop controller because this identifier contains other elements than the previous identifiers. The structure of the identifier FNIV, as shown in Fig. (6), for two stands only. The identifier has two inputs, which are the set points of two successive stands, while the single output of the structure represents the loop height between these stands.

Structure of the loop controller based one fully FNs is obvious in Fig. (7) for two stands only. The error between the height reference and the loop height is propagated through the loop identifier using back propagation learning algorithm.

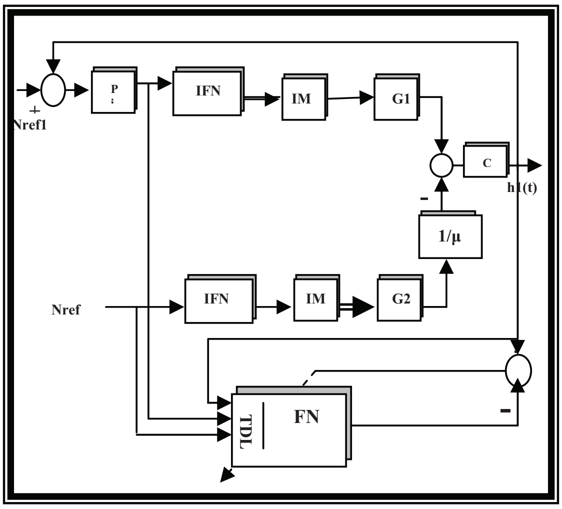

Fig. (6) Identification of loop controller with IFNC.

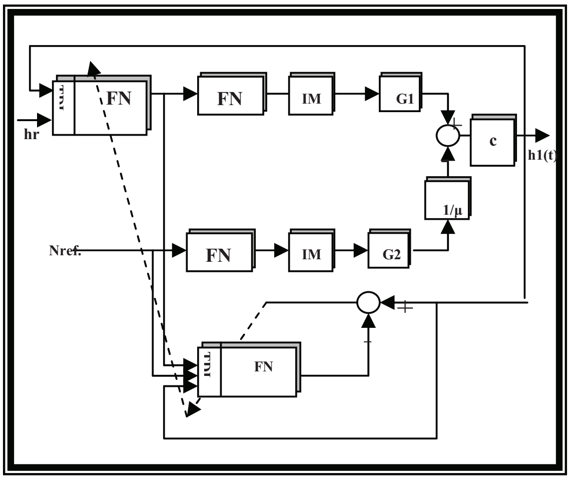

Fig. (7) Fully based FN structure for two stand

V. Simulation Results

In the simulation of a 100 hp induction motor used in each stand in steel rolling process, whose parameters are listed in Table (1). In the first part of simulation, the Fuzzt-Neural Inverse identifier is illustrated in Fig. (8) of loop hieght. For the fully Fuzzy-Neural Network (FNN) control structure, Fig. (9) represents the induction motor speeds responses of the whole rolling contains 10 stands, which shows undisturbed curves with parameter changes disturbance in stand 6 and the looper height changes between stands 6 and 7. While Fig. (10) shows the loop heights and their corresponding lengths. Torque loading is applied on stand 10, and the motor speed responses are illustrated in Fig. (11), and Fig. (12) for 14 stands.

Where the corresponding responses of the loop heights and their lengths are shown in Fig. (13).

Table(1): Induction Machine data 100hp	
Ls=0.0165	stator inductance
Lr=0.0164	rotor inductance
Lm=0.016	mutual inductance
Rs=0.095	stator ohmic resistance
Rr=0.075	rotor ohmic resistance
J=5	inertia moment

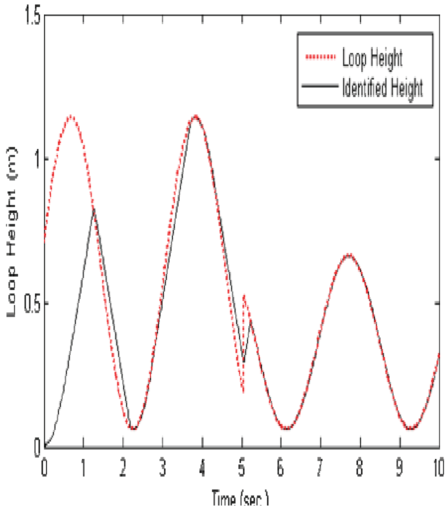

Fig. (8) First step responses for the loop height of FNIV.

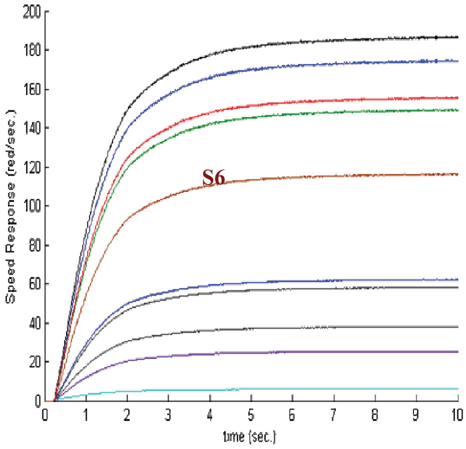

Fig. (9) Speed responses for viscous parameter change for fully-FN structure.

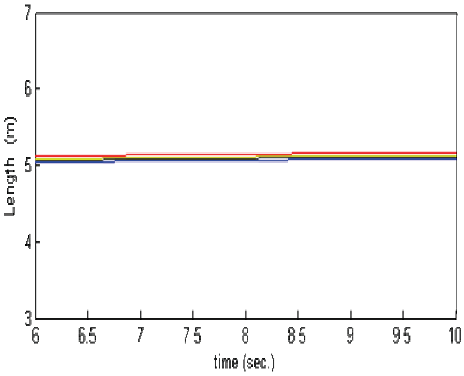

Fig. (10) Loop height responses for viscous parameter change for Fully-FN structure.

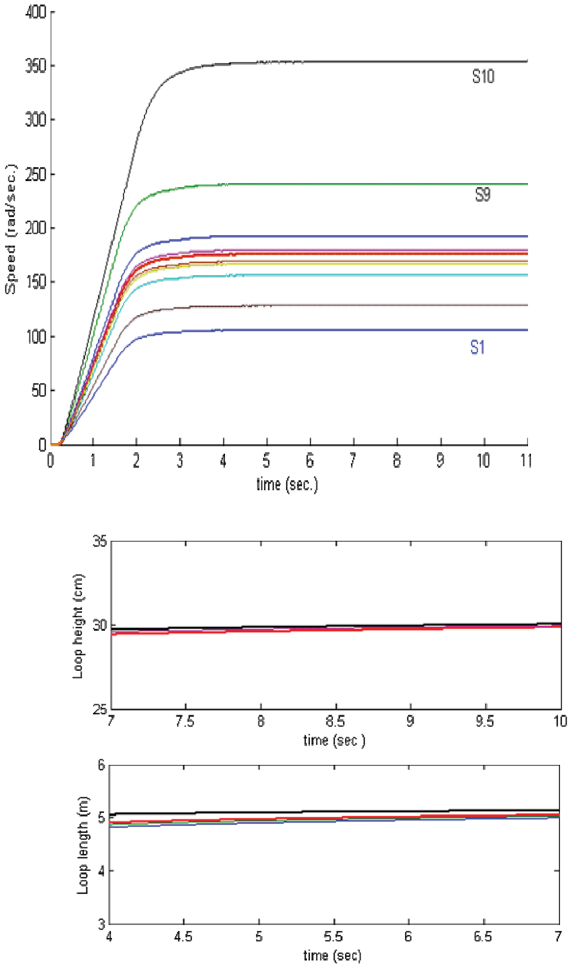

Fig. (11) Speed response, Loop height and Loop length responses for torque loading for fully-FN structure.

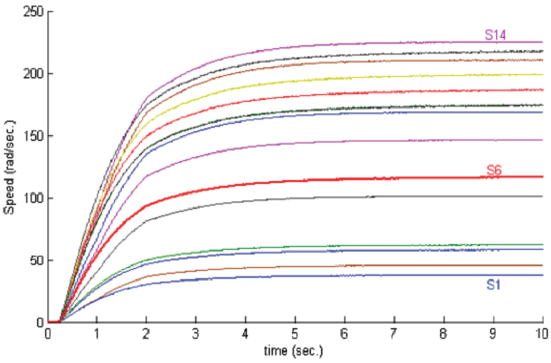

Fig. (12) Speed responses for 14-stands and parameter change for fully-IFN structure.

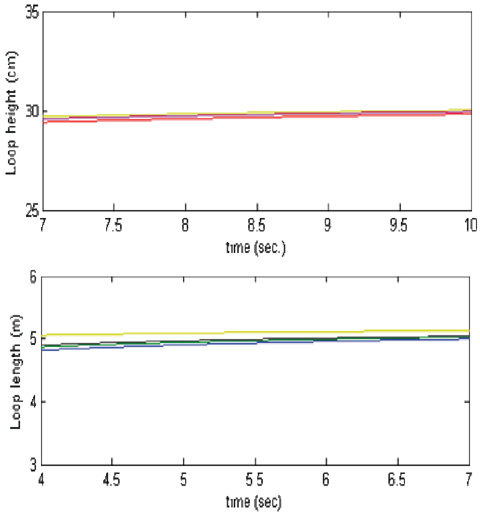

Fig. (13) Loop height and lengths responses for Fully-IFN structure.

VI. Conclusion

This paper presents some designed approaches to hybrid control architectures combining conventional control techniques with fuzzy logic and neural networks. Such hybrid structures lead to robust and easily tuned controllers. Sometimes, in practical rolling mills, the workers resort to use manual control when a disturbance occurs on the loop height. As in the previous examples, if the loop height between stand 6 and stand 7 is increased due to any change, the worker on the monitor position will run the manual control by decreasing motor speed of stand 6, which by the same rate all the downstream stands will respond to this increment. Therefore, the tracking process between the downstream stands is important to account. Those tests had been carried in this work depending on detecting the performance of the tracking between the stands.

As a comparative study between the proposed different structures with respect to the disturbance effects and time required to eliminate these effects, fully fuzzy-neural control structure is a good alternative.

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