Tension Control of a Winding Machine for Rectangular Coils

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Abstract--This paper introduces the design and testing of tension control prototype systems to minimise these tension variations, which includes a fluidic muscle powered take up arm, a fluidic muscle wire accumulator and felt pad. First the model and their limitations for existing tensioning systems are identified. Then, they are theoretically analysed in simulations. The simulation results show that the acceleration and deceleration of the wire due to the changing wire path length causes a cyclic tension fluctuation. An online tension sensor verified the predictions of the model. The key for a successful design is to remove tension variations. We propose to add a wire flattening machine which includes an accumulator and tensioning device, and replace the conventional pneumatic cylinder powering the accumulator with a fluidic muscle. The simulation shows that the new prototype system almost doubles the winding speed with a tolerable tension fluctuation.

I. INTRODUCTION

Thousands of transformers are manufactured each year in Australia. In conjunction with power stations, sub- stations, and power lines, the distribution transformers provide power to both commercial and residential applications right across the country. The manufacture of transformers involves the production of windings or coils. These coils are generally made up of a number of turns of copper wire in between layers of insulation paper. They are usually either round or rectangular. The coils are wound on a winding machine at high speed.

During coil winding a consistent tension is required on the wire. The shape of the coil being wound has a significant impact on the quality of the tension applied by the tensioner [1-2]. For a round coil the tension does not vary significantly during one revolution, but a rectangular coil causes the wire tension to fluctuate. As a rectangular coil is being wound, the speed of the wire feeding onto the coil accelerates and decelerates as the coil turns on the winding machine shaft [1-3]. This is shown in figure 1 below. This speed variation is due to the constantly changing wire path length. In the case of a round coil this is not a problem because the point of contact of the wire on the coil is fixed.

[Author's Accepted Version]

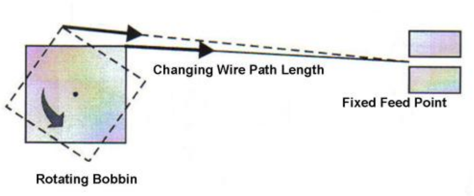

Figure 1: Acceleration due to changing wire path length during winding

The varying tension results in the loading on the machine traverse and main shaft to vary, leading to excessive forces and machine vibrations. This in turn can cause wire cross overs and variations in the coil. When these problems occur, it is a time consuming task to remedy [1, 4-5]. In addition, the coil production capacity of the plant is the limiting factor in the plant's overall capacity, so any interruptions to the output of coils limits the whole factory [1]. Common wire tensioning devices on the market today, only operate at around 5 m/s for heavy wire gauges and up to 30 m/s for very fine wire. Our regularly winds in excess of 10 m/s and is aiming to achieve at least 20 m/s for the entire wire range of 0.45 mm to 4 mm. An alternative solution is therefore sought, to maintain a constant wire tension while winding at high speed.

The research in tention control is much broader and applies to the general concept of tension control during the winding process, for both wire, net and sheets, and mainly for round bobbins. The work done on the application of tension control devices specifically for rectangular coils is minimal. Feldmann and Dobroschke [1-2] outlined that the tensile force variations are due to accelerations of the wire. This in turn is a result of the changing wire path length due to the shape of the bobbin. They go on to explain that most tensioning devices on the market today use a braked pulley with the wire wrapped around it as the means of transferring a tension force to the wire, and typically electric motors or magnetic particle brakes are used to control that. It was also highlighted that the frequency of a tension sensor used to physically measure the tension fluctuations needs to be ten times higher than the frequency of the disturbance or tension variation. Manning [4] stated that tension control devices fall into three main categories, namely mechanical, electrical, and computerised control. Of these devices the electronic or computer controlled device has the best response time. Feldmann and Wenger [3] detail the need for consistent wire tension when winding to produce quality coils. Experiments have shown that the selection and accurate control of the appropriate tension affects the overall dimensions of the coil. The quality control procedures of modern manufacturing processes have very tight tolerances, and thus strict control of tension must be maintained. Electronic tensioners commonly used in the industry are not capable of compensating satisfactorily for fluctuations caused by rectangular bobbins rotating at high speed. A solution to this was outlined by the use of a felt pad clamping system with a piezo-actor. This system has an extremely fast response time as no mass except the wire itself has to be moved during the winding process. The mechanical stress induced in the wire due to tensioning has to be kept to a minimum. The winding of the wire around a pulley or similar, to enable the use of a braking system, has the disadvantage of work hardening the wire and damaging the enamel coating. These types of systems also generally need to be controlled in closed loops because of their non-linear performance characteristics. Stangroom [5] demonstrates the application of electro-rheological (ER) fluids in a novel tension control concept. Electro-rheological fluids are slurries made of a suspension of finely divided solids, in an oily base liquid. These liquids, when exposed to a high voltage electric field, solidify. They can go from liquid to solid in under a millisecond. The control concept involves using the ER fluid as a fast response actuator for driving a motor which controls the winding speed. The actuator is driven by a tension pulley. This system still has the draw back of high inertia due to trying to control the rotating coil itself. Manning [4] describes the purpose and function of tension as giving the winding machine maximum control of the wire, hence creating a quality coil and getting maximum performance from the machine. The pretension is defined as the tension applied to the wire, before and after the tensioning device, and is caused by the friction of the wire running over eyelets, guide pulleys and the supply spool flange. Manning [4] continues on to describe various control options, recommending closed loop, electronic, programmable tension devices as the best solution because they monitor winding tension and have a fast response time. However they are generally only suitable for lighter wire gauges and are very expensive.

This paper further investigates the tension fluctuation problem and to achieve a consistent wire tension while winding a rectangular coil at high speed. In the following section issues of the winding processes are described, and the available techniques for tensing are reviewed. Modelling considerations and system identifications are provided in section 3. Section 4 contains a description of the prototype system design and implementation. In section 5 the experiments and analysis are carried out. The conclusion and findings are given in Section 6.

II. BACKGROUND

The existing winding system shown in figure 2 uses felt pads for tensioning. The spool of wire to be wound is mounted into its housing vertically and the wire is fed up through the wire guide and felt pads, over the guide pulley and then to the winding machine. The tension is varied by tightening or loosening the large g-clamp.

Figure 2: Existing wire mounting and tension setup

Felt pads are one of the simplest and most commonly used wire tensioning methods.

The photo in figure 2 shows the main components and principle of operation. The configuration shown above uses a g-clamp to apply a squeezing force to the felt pads. The wire is passed through the felt pads and hence some of the force applied to the felt pads is also applied to the wire. In operation, the wire travels through these felt pads and the retardation or tension force is created by the friction of the surface of the enamel coated wire rubbing on the felt pads. The machine operator threads the wire through the guides and pulleys and adjusts the clamping force manually and intuitively. The advantages are: simple and readily available; inexpensive; adaptive to any operating speed. The disadvantages are also obvious. The Pads wear out quickly leading to loss of tension, the applied force is only generally independent of speed, need to be tightened and replaced frequently, intuitive tension setting does not allow good quality control and no compensation for bobbin shape.

A. New Tensioning System Requirements

The new tensioning system needs to meet the following:

- Accommodate a range of wire sizes from approximately 0.5 mm to 4 mm in diameter.
- Suitable for both rectangular and round cross-sectional wire.
- Easy for the user to setup and operate.
- Consistently adjustable to various tension settings.
- Operate at high speed i.e. 1000 RPM.
- Have a response time of 5 ms or less.
- Be compatible with the existing winding machines.

Ideally, the device will operate at any wire speed up to 20 m/s, and will perform regardless of the wire size or tension applied. The device(s) is/are also required to apply a specific tension to the wire that can be set by the user. This needs to be unaffected by wire speed and should be easily and consistently adjustable to required settings. The setup needs to be designed and mounted in a single, easy to use unit which can be adapted onto any winding machine. A cost/benefit study needs to be undertaken including the measured improvement in the consistency of the wire tension. Therefore, a method of measuring the tension variations before and after the device has been installed, is required.

B. Existing Techniques for Tensioning

Tension control can also be implemented through control the speed of the winding. A typical system is shown in the diagram figure 3 below. The system shown continually monitors the wire tension through a tension pulley connected to a spring. The position of the pulley is output to a controller which compares this tension with the preset tension and drives the motor accordingly, speeding up for a drop and slowing down for an increase in tension.

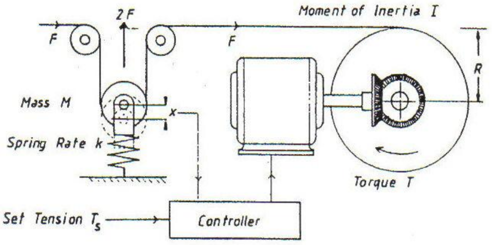

Figure 3: Basic winding speed tension control system

There are many mechanical tensioners commercially available today. They nearly all involve winding the wire around a pulley, which is braked in some way, and then running it over a take up arm. To create tension the system uses the braked force of the pulley applied to the wire by friction.

The pneumatic cylinder is the most common method of powering wire accumulators used in tension control. An accumulator is two sets of pulleys, one fixed and one adjustable, with wire looped between them, traveling across them, so there is one entry point and one exit point. A typical product available is shown in figure 4. The main reason for using a wire accumulator in conjunction with any tensioning device is to act as a compensator, and improve the response of the tensioner. The adjustable set of pulleys are connected to a pneumatic cylinder which reacts to the amount of tension placed on the wire. The pulleys then move to shorten (create slack) or lengthen (take up slack) the wire path according to the preset tension. The principle of any accumulator is that a small change in movement of the adjustable pulleys results in a large change in wire path length, hence only a small reaction is needed to maintain constant tension. The tension is still applied separately, by mechanical means such as a braked pulley. The accumulator is purely a compensating device for the changing wire path length and speed. In applying tension with either a hysteresis, magnetic particle, or pneumatic disc brake, the brake first needs to be coupled to a pulley, usually by way of a shaft. The pulley then has the wire wrapped around it and the braking torque is applied to the wire through the friction of the wire on the pulley.

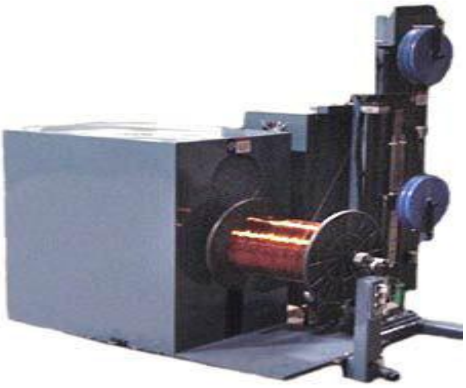

Figure 4: Commercially available constant tension dereeler with accumulator

The electronic tensioner is becoming a more popular device because of the increase towards the complete automation of winding machines. Modern winding machines are computer or PLC controlled which lends itself to interfacing an electronic tensioner with the system and allowing the program to control tension, giving better quality control. Typical products available are shown in figure 5.

The closed loop system continually monitors the wire tension and feeds back the value to the controller, for continual adjustment resulting in constant tension. The open loop system is just a set and leave system with no real time tension measurement. The device uses an electronically controlled magnetic brake, which applies a resisting torque to felt coated pulleys. The system has a very fast response.

Figure 5: Commercially available open and closed loop electronic tensioners

III. MODEL IDENTIFICATION

The wire travels from the spool through the tensioning device, over the machine traverse, and onto the rectangular coil. The system was simplified as shown in figure

1 to just be a fixed feed point, where the tension is applied, and a rotating rectangle representing the bobbin or coil.

The desired operating speed is 1000 RPM. This gives a wire speed of 10 - 30 m/s depending on the coil size at a particular instant in time. The fixed point used in the model is a distance of 100 mm in x-direction and 100 mm in the y- direction from the top right hand corner of the bobbin. The bobbin size used here is 200 mm by 150 mm, a typical starting size used in the factory. The bobbin starts in a horizontal position aligned with the x and y plane. The aim of the model is to simulate, so as to understand, the motion of the wire. Figure 6 shows the variation of the wire velocity produced by the rectangular shape of the bobbin. As the coil increases in size during winding, the general shape of the graphs below do not change, only the magnitude of the minimum and maximum velocity and acceleration increase as the coil grows. As the wire speed decreases slack is going to be created, hence the tension will be decreasing. When the wire is speeding up, any slack will be taken up and the tension increased. This means that a plot of the tension variation will look very similar to the velocity graph, the only difference being that the y-axis will have a different scale and show tension values. The general shape of the graph will remain unchanged. Figure 7 shows the variation of the wire acceleration, which can also be seen by the slope of the line or derivative of the velocity graph.

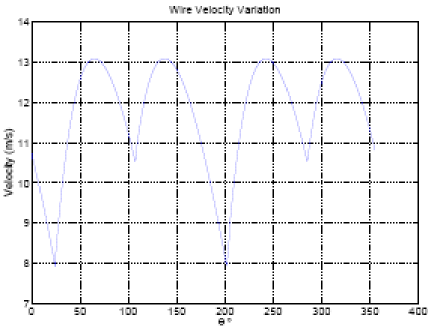

Figure 6: The wire velocity variation for one revolution with a former size of 200 by 150

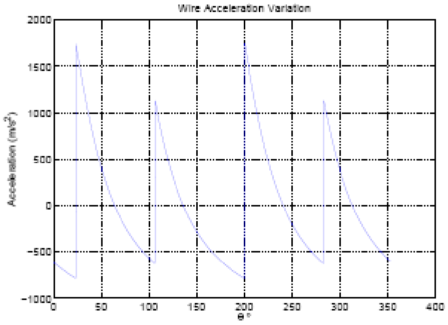

Figure 7: The wire acceleration variation for one revolution with a former size of 200 by 150 mm.

This 1000 RPM frequency is relatively low, however it is these rapid changes in velocity that are the limiting factor when trying to get a device to compensate for the fluctuating tension. Using MATLAB the individual durations of each acceleration and deceleration segment were calculated. They are summarised in table 1.

Table 1: The duration of acceleration and deceleration segments.

Segment	Approximate Duration (ms)
1	4.15
2	6.68
3	7.07
4	5
5	11.25
6	6.68
7	7.07
8	5
9	7.1
Total	60

From table1 it can be seen that the wire speed variations occur very quickly. The partial segments 1 and 9 combine to make a whole segment identical to segment 5. This is due to the bobbin's starting orientation. The bobbin starts a little way through its deceleration segment. The rapid wire speed and hence tension variations are directly related to the change in wire path length. The wire path length variation, from the fixed feed point to the wind on point, is shown in figure 8 below.

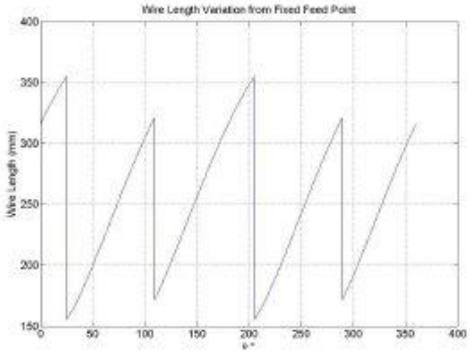

Figure 8: The wire length variation for one revolution with a former size of 200 by 150 mm.

IV. PROTOTYPE SYSTEM DESIGN

The system in figure 9 incorporates a relatively new pneumatic device called a fluidic muscle. The muscle is made of a woven, flexible material and operates under air pressure. Under pressure it expands laterally and contracts longitudinally. A preset pressure determines the maximum and minimum forces it will apply for a specific contraction. The muscle is very similar to a conventional pneumatic cylinder, except it has a very fast response and is highly dynamic, not unlike a spring. It also acts in tension and not compression, and can apply 10 times more force than a conventional pneumatic cylinder of the same diameter. The muscle controls a dancing arm which moves to take up and release the slack in the wire. This pressure is set to accommodate the range of wire tensions required.

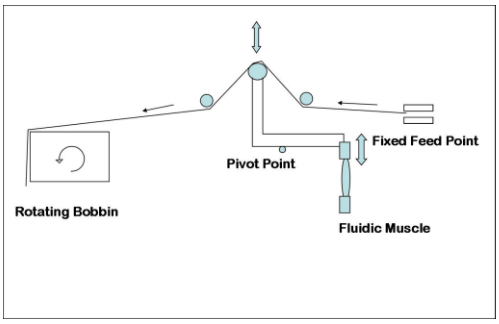

Figure 9: Fluidic muscle powered dancing arm.

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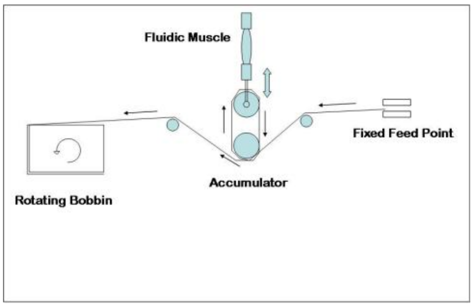

Figure 10: Fluidic muscle powered accumulator.

The fluidic muscle powered accumulator prototype system is shown in figure 10, where the pneumatic cylinder used in the accumulator is replaced with a muscle, otherwise the operation is the same as outlined previously.

To verify the theoretical model using the above prototype systems an online tension sensor was purchased from Germany. The sensor is made up of a shaft with a pulley mounted on it for the wire to run over, a main body housing a strain gauge and a connection to an output lead and plug. A mounting bracket was made to allow the sensor to be placed in position. The tension sensor uses the strain gauge to convert a mechanical deflection into an electrical signal output. This output is then scaled and converted into a tension value. The tension sensor was setup on the winding machine to allow the wire to travel over the pulley. To obtain more accurate results a data logger was hired for two days. A number of difficulties were faced when using the data logger to verify the theoretical model. The signal output was very noisy. This could have been due to many things such as electrical interference from machines and equipment in the factory, or the internal signal filter of the data logger not working properly, or the resolution of the data logger not being small enough. The latter was probably the main reason as the measurements made were commonly less than 1 mV and the signal generated with no load on the sensor had an approximate range of 0 to 0.1 mV. For a 1 mV output this shows that up to 10% of this could be noise.

While the signal was noisy, the tension variations can be clearly observed. The signal shown is in mV, which translates into a tension range of approximately 74 N to 83 N for the 1.5 mm wire used in the test.

V. EXPERIMENT RESULT AND ANALYSIS

The tests were carried out to observe the response using the above constructed prototype system.

Fluidic Muscle Powered Dancing Arm: At low speed the arm responded initially but operated in long sharp jerks, not smooth side to side movements as expected. The wire appeared to vibrate more with the dancing arm, than without. At the end of winding one layer the resting position of the arm moved from its initial position inward approximately 300 mm. At high speed the arm did not respond, but just vibrated about a mean position.

Fluidic Muscle Powered Accumulator: The trial of a large muscle powered accumulator gave the following results: At low speed the accumulator did not appear to respond at all. Varying the pressure made no significant difference, other than pull the wire through the felt pads. At high speed the accumulator did not respond. With no response from the accumulator the whole system vibrated, making the wire and traverse vibrations increase.

The tension sensor data collected before the accumulator was used is shown in figure 11. The maximum and minimum tension is approximately 62 N and 46 N respectively.

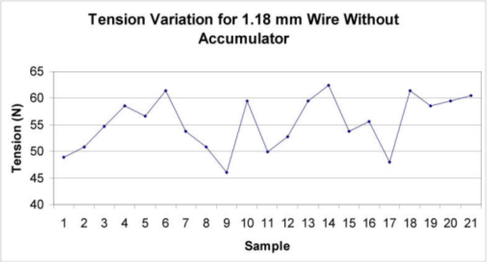

Figure 11: Plot of tension sensor output without the accumulator

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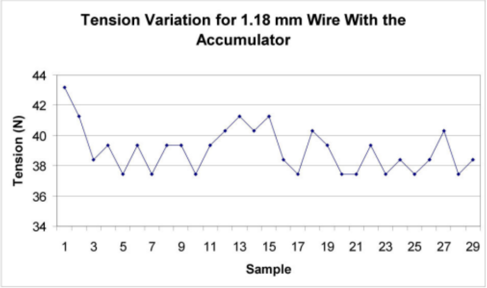

Figure 12: Plot of tension sensor output with the accumulator.

The tension sensor data collected when using the accumulator is shown in figure 12. The maximum and minimum tension is approximately 43 N and 37 N respectively.

A. Fluidic Muscle Powered Dancing Arm Performance

As a result of the operation of the system being not as expected, explanations were sought to correct the behaviour. At low speeds, the dancing arm moved outwards extending the muscle, keeping the tension force in the wire. Then it reached the point where the arm force equaled the force applied by the felt pads and at this point the arm force overcame the friction force from the felt pads and jerked inwards rapidly, pulling the wire through the felt pads. Increasing the felt pad pressure and lowering the pressure in the muscle made no difference. The felt pads wear out very quickly. The tension applied at the beginning of a layer can be significantly higher than the tension at the end of the layer. Even if the pads did not wear out the frictional force applied by the felt pads is not constant as friction is only ’generally’ independent of speed, and the wire speed is continually changing. As this friction force changed the dancing arm overcame it at different points and pulled the wire through the felt pads instead of compensating for changes between the fixed feed point at the felt pads, and the changing feed on point at the bobbin. The force applied at the felt pads always needs to be greater than the tension force applied by the arm otherwise the system will not work. The system relies on the principle of having a constant tension applied regardless of the speed. The system needs the fixed feed point to slip at a constant rate. If one of the points in the system is moving at a constant rate then the arm can compensate for variations in the rate of change of the other point, which is the feed on point in this case. If both the points are varying at different rates the dancing arm has no reference value and will not compensate for any changes.

Other limitations with the setup were: Setting the pressure in the muscle to match the desired tension for the wire was not exact, but not a significant problem to impede the general operation of the system. The arm had to be strong enough to withstand the maximum forces applied to it. Although the weight was low, the inertia of such a large arm limits the maximum winding speed. A different tensioning system is needed for the dancing arm to work. For example, hysteresis brakes that apply a constant torque independent of speed would overcome this problem. It is concluded from the experiment that the main reason this did not work, even at low speed, was the non-linear performance characteristics and wearing of the felt pads.

B. Fluidic Muscle Powered Accumulator Performance

The muscle that was originally sized for the dancing arm operation was used in the first accumulator setup. The trial indicated that the muscle was not sized correctly as it did not respond at all, even after varying the muscle pressure. Large forces were required to activate the muscle, therefore it was concluded that the sensitivity was too low. This was confirmed after approaching Festo, the supplier of the muscle. Their recommendation was to resize and select a new muscle for the accumulator. The smaller muscle was more sensitive and better sized for this application. As a result, the system performed much better reacting to the smaller forces required. Although, the same problem with the frictional force, applied by the felt pads, varying occurred, this system was not affected as much as the dancing arm system. This was due to the smaller forces involved and the effect the accumulator had of magnifying a small force and length change by the muscle to a larger one in the wire. The muscle was able to detect the mean tension change due to the felt pads wearing out and adjust its initial position. Even though visually the wire vibrated more, it did not mean that the tension fluctuations were greater. The small but significant decrease in the tension fluctuations can be seen from figure 11 and figure 12. The range decreased from 16 N to 6 N. This showed that the system worked to a degree. While observing the experiment, it also showed that even small tension variations can still cause significant vibrations in the winding machine parts. The felt pads, along with inertia, are the main limitations with this system. The felt pads still wear out and the tension force applied is varying with speed. This results in the accumulator pulling the wire through the felt pads, though not as much as with the dancing arm. The tensioning system needs to be changed to apply a constant force independent of speed.

VI. CONCLUSIONS

Rectangular coils are important part of distribution transformers. When winding these coils the wire tension fluctuates due to the coil shape. These fluctuations lead to wire breakages, inconsistent coil dimensions, excess machine wear, limit on the maximum winding speed and transformer failure in the field. From our comprehensive research into existing tensioning systems, none of them are ideally suited to fulfil our requirements although the fluidic muscle accumulator was found to be the most suitable option to develop as a compensator. As the current tensioning system, felt pads, are not suitable for interfacing with a compensator, the decision to add a wire flattening machine is made based on out experiment and simulation results. The intuitive process of setting the tension using a g-clamp does not allow consistency, therefore affecting quality control. Therefore, a wire flattening machine recommended with the feasibility of using the muscle in place of the cylinder. The new winding machine will almost double the current winding speed and result in a big annual saving (estimated about $59,100 for each machine. The inclusion of a new tensioning system can apply up to 500 N constant tension force without generating a large amounts of heat, and overcomes the current problems associated with friction.

REFERENCES

[1] Cary Stapleton, "Winding Machine Tension Control", Dissertation, Faculty of Engineering and Surveying, University of southern Queensland, QLD, Australia, Dec., 2005

[2] K. Feldmann & D. Dobroschke, 'Innovative approaches for optimising tension control', International Coil Winding Journal 2004.

[3] K. Feldmann & U. Wenger, 'Optimization for wire tensioners', Proceedings: Electrical Manufacturing & Coil Winding Association Conference . 2001.

[4] T. Manning, 'Tension control during the coil winding process', Proceedings: Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Association Conference, Apr. 2005.

[5] J. Stangroom, 'Tension control - new approaches', Wire Industry 59(697), 33–3, 1992.

[6] Anne Angermann, Maik Aicher & Dierk Schroder, "Time-optimal tension control for processing plants with continuous moving webs", 2000 IEEE Industry Applications Conference Proceedings, pp. 3505-3511, Vol 5, Oct. 8-12, 2000, Rome, Italy.

[7] B. H. Freyer, I. K. Craig & P. C. Pistorius, "Gauge and tension control during the acceleration phase of a steckel hot rolling mill," ISIJ International, Vol. 43, No. 10, pp. 1562-1571, Oct. 2003.

[8] Brain Thomas Boulter, Y. Hou, Z. Gao & F. Jiang, "Active disturbance rejection control for web tension regulation and control," 2001 IEEE Conference on Decision and Control Proceedings, Vol. 5, pp. 4974-4979, Dec. 4-7, 2001, Orlando, FL, USA.