Overview of Slip Control Methods Used in Locomotives

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Abstract — **Modern locomotives are more powerful and reaches higher speeds. With these parameters increasing it is connected a problem with transmission of the tractive effort between vehicle wheels and rails. The maximum value of the transmitted force depends on value of the wheel slip velocity and its type of control. In the paper problem of the force transmission and some used control methods are briefly described. The simulation in Matlab/Simulink is also one of the described methods.**

Keywords — adhesion characteristic, slip, slip control, tractive effort

I. Introduction

Total locomotive tractive effort depends on the sum of individual tangential forces that are transmitted by every wheel. The maximum value of the tractive effort can be achieved when a slip velocity of every driven wheelset is controlled to an appropriate value. Therefore the slip velocity has to be controlled by a slip controller or limited by re-adhesion controller. The slip controller instead of increasing the maximum tractive effort can e.g. decrease power losses, decrease wear of the wheels and rails or can avoid mechanical damage of the locomotive. Used slip control methods are very different from simple methods that compare wheels circumference velocities with thresholds to sophisticated neural networks. The methods use a broad knowledge of electrical engineering, control technology and mechanical engineering.

The paper describes methods that are used in locomotives. Instead of locomotives similar methods are used in Electric Multiple Units (EMU). There are some differences between slip control methods for locomotives and EMUs. The slip controllers for EMUs aim to prevent high value of the slip velocity and therefore reduction of power loses and wears of vehicle wheels and rails. The slip controllers for locomotives aim to achieve maximum tangential force between wheels and rails [1]. The lower tangential forces between wheels and rails are compensated by greater amount of driven wheelsets and the tangential force cannot be high due to higher vehicle adhesion weight. The locomotives have to have higher slip velocity to achieve higher tangential forces between wheels and rails [1]. The tangential force has to be higher due to lower adhesion weight.

The paper is divided into four parts. In the first part basic terms that are connected with slip control are briefly described. The most important terms are tangential force and adhesion coefficient and its relation. In the second part are described some control methods that are used in locomotives are described. The methods are divided into six groups according of its working principle. In the first group there are older methods that controls slip velocity to a constant value. In the second group methods that controls adhesion coefficient at the maximum value are presented and in the third group methods that use a speed controller for slip control are described. In the fourth group methods that determines slope of an adhesion-slip velocity characteristic are introduced. In the fifth group it is described indirect method that uses locomotive dynamic motions to detect value of the slip velocity. In the last group it is described hybrid slip control methods that uses combination of more slip control methods to achieve better results. In the final part of the paper there are shown simulation results of the method that control slip velocity on principle that uses speed controller properties. The simulation is showing reaction of the controller to a high value of the slip velocity and operating point moving on the adhesion characteristic.

II. Force Transmission between Wheels and Rails

The force that is transmitted between wheels and rail is called the tangential force. The tangential force is transmitted by a small contact area between the wheel and rail having area of a few square centimetres [2]. The maximum value of the tangential force depends on the adhesion coefficient and the locomotive adhesion weight. Both parameters vary in time and locomotive position on the track. The adhesion coefficient depends on the slip velocity, conditions of rail surface, a train velocity and temperature in the contact area.

From parameters that can influence the adhesion coefficient only the train velocity and slip velocity can be changed and controlled. Because the train velocity is typically maintained on the required value then only slip velocity is appropriate to control. All significant forces and velocities that act on a wheel are shown in Fig. 1.

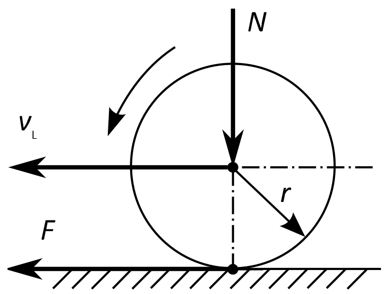

Fig. 1. Forces and velocities that act on wheel

The slip velocity has to be defined for every wheel:

$$v_{si} = v_{wi} - v_{Li} \tag{1}$$

Where v_{si} is wheel slip velocity of wheel *i*, v_{wi} is circumference velocity of wheel *i* and v_{Li} is longitudinal velocity of wheel *i*.

Sometimes it is used a slip *s* instead of the slip velocity. The slip is defined:

$$s_i = \frac{v_{si}}{v_{Li}} \tag{2}$$

Because the wheels in one wheelset are rigidly connected then velocity of the wheelset is controlled. Although the velocities are different due to e.g. wheels conic different wheel diameter and torsion of axle. Instead of the wheel longitudinal velocity it is typically used train velocity.

The dependence of the adhesion coefficient on the slip velocity or slip is called an adhesion-slip characteristic. An example of the characteristic is shown in Fig. 2. The characteristic is divided into three areas. The first area is called a linear area. In this area the adhesion coefficient depends approximately linearly on the slip velocity. The second area is called nonlinear area. Both areas are called as a stable area of the adhesion-slip characteristic and the area is from zero value of the slip velocity to approx 2 km·h-1 [3], [4]. The third area is called the unstable area. The goal of the slip control is to keep the slip velocity in the linear area of the characteristic in EMUs and in the stable area or not far from the peak value in the unstable area of the locomotive characteristic [1]. The slip velocity affects value of the adhesion coefficient from zero to its maximum value. The conditions of the rail surface, a train velocity and temperature of contact area affects the maximum value of the adhesion coefficient and the slip velocity in which the maximum of the adhesion coefficient occur. Second parameter that affects value of the tangential force is the adhesion weight that is changed. The change occurs when the locomotive e.g. pitches, bounces or moves through a switch or crossing.

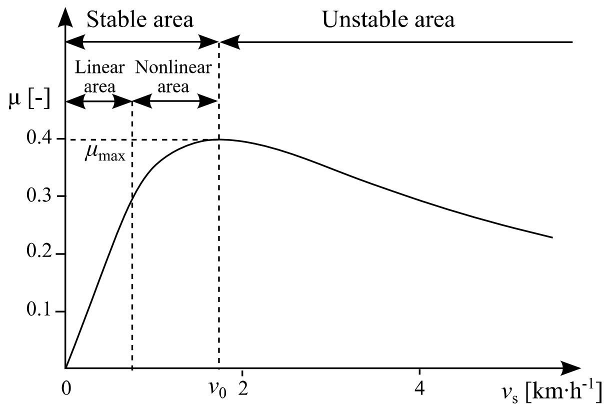

Fig 2. Example of the adhesion-slip velocity characteristic shape

The slip velocity influences value of the adhesion coefficient on the current adhesion-slip velocity characteristic that is set by the rail conditions, train velocity and temperature. The rail conditions affect the maximum value of the adhesion coefficient and the shape of the characteristic. In Fig. 3 it is shown an example of the characteristic changes in different conditions of the rail surface. The third parameter is temperature of the contact area. With increasing temperature the value of adhesion coefficient is increased too. The last parameter is a train longitudinal velocity that affects the maximum value of the characteristics. For calculation of the dependence a known equation according e.g. Curtius and Kniffler of Kother can be used. The maximum value of the adhesion coefficient decreases when the longitudinal velocity increases. The dependence according Curtius and Kniffler can be expressed:

$$\mu_{max} = \frac{7.5}{v_L + 44} + 0.161 \tag{3}$$

The tractive effort of the whole locomotive can be calculated as sum of partial tangential forces of all driven wheels. This calculation is necessary because every wheel has different adhesion coefficient and different adhesion weight.

$$F = \sum_{i=1}^{n} \mu_i \cdot W_i \cdot g \tag{4}$$

Where *F* is locomotive tractive effort, μ_i is an adhesion coefficients for wheel *i* and W_i is an adhesion weights that are applied on the wheel *i*, *n* is total number of driven wheelsets and *g* is the gravity acceleration.

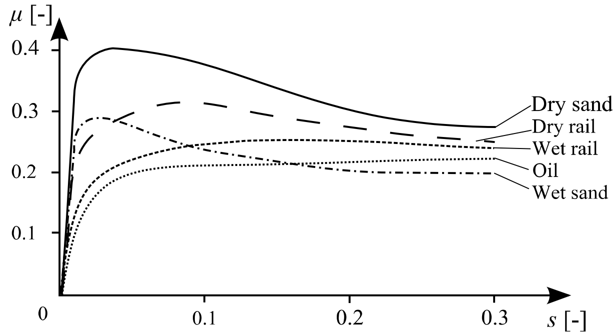

Fig 3. Changes of the adhesion-slip characteristic on railway conditions [5]

III. Overview of Slip Control Methods

Methods described in the literature are divided into many groups. Some method division is described in [1] where the methods are divided according the target vehicle. Another division is suggested in [6] where the division is done according principle of the method operation. Methods are divided into six groups in this paper. The methods are based on some different principles like control of the slip velocity to a constant value, or control of the slip velocity to achieve maximum value on the adhesion-slip velocity characteristic or determination of the characteristic slope and according the slope control of the slip velocity. Instead of suggested methods e.g. fuzzy logic, neural network or evolutionary algorithms [7] are described in literature. Every method has some advantages and some disadvantages therefore methods are sometimes combining to hybrid slip control methods to eliminate the individual method disadvantage. Some older slip control methods were based on the slip velocity control. But determination of the true slip velocity is difficult because when the wheel velocity is measured only on driven wheels it is difficult to determine the wheel circumference velocity and train longitudinal velocity. Therefore some improvements like accelerometers, GPS or Doppler radars or its fusion are used [9]. But using these velocity resources causes additional errors. Required accuracy of the slip velocity is a second problem because the accuracy of the determined slip velocity should be around 0.1 km·h^{-1} [7]. Therefore newly developed methods try to control slip velocity according another parameters or try some parameters estimates. Some methods do not use the slip velocity or electric drive parameters but use some other parameters. These methods are called indirect method and the methods use e.g. torsion vibration or noise to control tangential forces to an achieved value. The methods are based on assumption that the high value of the adhesion coefficient damps dynamic motions [9]. But these methods are not widely used and the methods are in experimental development.

A. Methods Based on Slip Velocity Control to a Constant Value

The methods are older ones. The methods have many variants but the basic principle is the same. The methods are based on control of the slip velocity at a constant value. The methods were used on locomotives with DC motors and many of them are still in service. The methods are outdated however there are many descriptions and measurements on locomotives with the methods.

The methods are based on assumption that the maximum value of the adhesion coefficient occurs approximately at the same slip velocity. Different conditions of rail surface influences the maximum value of the adhesion coefficient and change slip velocity in which the maximum value of the adhesion coefficient occurs. An example of the difference is shown in Fig. 3. According some measurement the maximum value of the adhesion coefficient occur bellow 2 km·h^{-1}. The main disadvantage of methods is that methods need to determine the slip velocity for every wheelset. The wheels circumference velocity can be measured by incremental encoders that are typically mounted in every driven wheelsets. But the wheel longitudinal velocity or train velocity is difficult to determine. The longitudinal velocity is typically determined as a velocity of the slowest wheelset or a pseudo axle is used [3]. In some cases the velocity can be determined by measuring on non-driven wheelsets. This solution is typical for EMUs. The method block diagram is in Fig. 4. The threshold has to be set in the stable area of the adhesion-slip velocity characteristic near the maximum value of the adhesion coefficient. The requirement is difficult to fulfil because the shape of the characteristic changes. If the threshold is set in a low value with the method it is difficult to achieve the maximum tractive effort and if the threshold is set in a high value in unstable area of the characteristic the method can cause large tractive effort ripple or can fail if the control loop is not sufficiently fast. The method can fail when the adhesion-slip velocity characteristic has a plateau and low adhesion coefficient or when all wheels has the same high slip velocity [7].

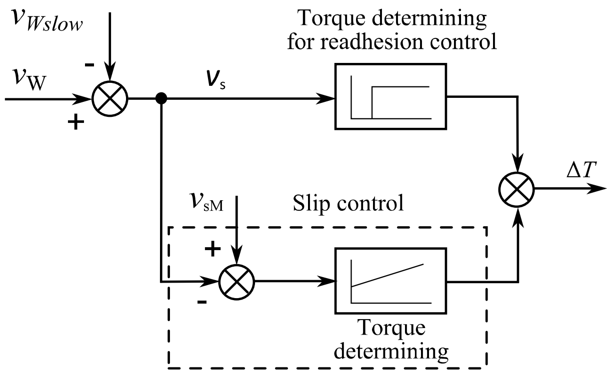

Fig 4. Block diagram of the method that controls the slip velocity to a constant value [3]

B. Methods Based on Searching Maximum Value of the Adhesion Slip-Velocity Characteristic

Methods in this group control the slip velocity to achieve the peak on the adhesion-slip characteristic. The main problem is to determine when the peak is achieved. Most of the methods are based on principle that the derivation of the tangential force or adhesion coefficient changes sign when the operating point moves over the maximum point on the characteristic. In some cases the characteristic can have a plateau instead of peak and the methods can fail because the sign is changed when the slip velocity has large value (e.g. curve for oil in Fig 3). Therefore the methods are typically supplemented by some other slip control methods to avoid readhesion control acts.

A way to find out the maximum value is to derivate the adhesion coefficient according the slip velocity or wheel acceleration according the force that corresponds with a motor torque. When the derivation is positive an operating point is in the stable area of the characteristic. If the derivation is negative the operating point is in the unstable area of the characteristic and when the derivation is zero the operating point is in the peak of the characteristic. The method needs not to determine train velocity but the adhesion coefficient or wheel acceleration needs to be known. Wheel acceleration is calculated as the derivation of wheel velocity. The coefficient cannot be measured but the coefficient has to be estimated:

$$\hat{T}_L = \frac{a}{s+a}\left(T_m - J_m \cdot s \cdot \omega_m\right) \tag{5}$$

where T_L is estimated load torque, J_m is a motor moment of inertia, ω_m is a motor angular speed, T_m is a motor torque and a is a low pass filter cut-off frequency.

From estimated load torque the adhesion coefficient can be calculated but it is inappropriate because the tangential force is given by product of the adhesion force and adhesion weight. The adhesion coefficient is changed therefore it is appropriate to estimate the tangential force directly because the adhesion weight is variable. In this case the disadvantage of change of the adhesion weight is eliminated.

The disadvantage is that the methods work behind the maximum point in the characteristic and the method periodically works in the unstable area of the adhesion-slip characteristic. The method disadvantage is that it causes inconsiderable motor torque ripple that is undesirable.

C. Methods Based on Speed Controller

Method in the group uses a speed controller to achieve the maximum value of the tangential force. The control method based on speed controller can operate in any part of the adhesion-slip velocity characteristic. The simple block diagram of the method is in Fig. 5. The method is different from other methods because the method does not use a torque controller to control the slip velocity as other methods. But the method uses a speed controller. Principle of the method is described in [10] in detail. The described method has improved control logic.

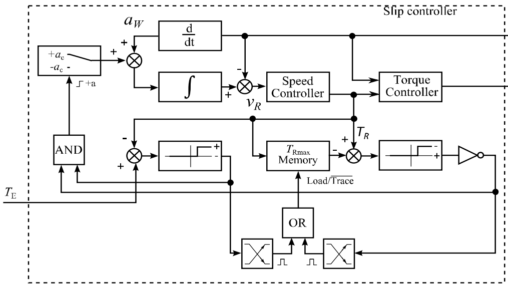

Fig. 5. Block diagram of the method that uses a speed controller for slip control

The motor torque T_R is lower than the required torque T_E and the constant acceleration is positive at the beginning of regulation. The constant acceleration a_c is added to wheel acceleration a_w and the required wheel velocity v_R is calculated. The velocity is used by the speed controller that calculates required motor torque T_R. The torque is led to the torque controller and to the slip controller logic. There are two cases that can occur during control. In first case the required torque T_R is lower than torque that corresponds with maximum tangential force that can be achieved on the current adhesion-slip velocity characteristic. It means that the operating point is in the stable area of the characteristic. In the case when the motor torque T_R is higher than the required torque T_E the sign of constant acceleration is changed to negative and the torque T_R starts to decrease. When the torque T_R is lower than torque T_E the sign of constant acceleration is changed to positive and the operating point oscillates around the T_E value. In the second case the required torque T_R is higher than torque that corresponds with maximum tangential force that can be achieved on the current adhesion-slip velocity characteristic. In this case the sign of the constant acceleration is switched according difference between the current required value of the motor torque T_R that is set by speed controller and maximum value T_{max} of the torque that was achieved. The T_{max} value is stored in tracking memory. In the stable area of the characteristic maximum value from tracking memory is equal to the required value but when the operating point comes across the characteristic peak value the torque will achieve its maximum possible value and this value is stored in the tracking memory. Next required value that is set by controller is lower than the maximum value and the difference causes switching of the sign of constant acceleration to a negative value. Required motor torque T_R stars to decrease and when the operating point gets to the stable area the difference changes the sign and the acceleration too. The operating point starts to oscillate around peak value of the adhesion characteristics.

The value of a constant acceleration is the main problem of the method because the acceleration has to be set to achieve high train acceleration for different load.

The method has the same disadvantage as previous methods because the method has to work in the unstable area of the characteristic. The method can work stably in any part of the characteristic in theory. But working in the unstable area causes a large motor torque ripple. The methods need fast control loop to work correctly in the unstable area of the adhesion characteristic.

D. Methods Based on the Adhesion-Slip Velocity Characteristic Slope Determination

The method in this group determines position of the operating point on the adhesion-slip velocity characteristic from the slope of the characteristic. The slope can be determined e.g. from the motor torque and motor angular speed phase frequency characteristic [3].

The method added a small sinus torque to the required motor torque. When the sinus torque is added the motor torque and speed become to oscillate. An angle for a phase frequency characteristic can be calculated from the oscillation. The position of the operating point on the characteristic depends on the calculated angle. The required torque is calculated as sum of the required torque and sinus torque.

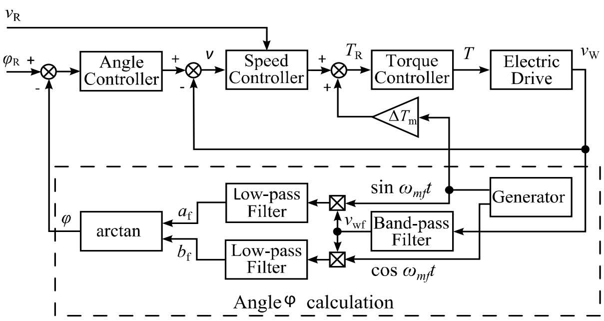

Fig. 6. Block diagram of the method that determines a slope of the adhesion-slip velocity characteristic [3]

Block diagram of the method is in Fig. 6. The wheel velocity v_w is measured by an incremental encoder. The measured signals contain noise. Therefore the signal is filtered by a band-pass filter. A filter output is multiplied by a sine wave and cosine wave with a modulation frequency. The signals are filtered by low-pass filters and from filter output an angle φ is calculated.

The main disadvantage of the method is that the sinusoidal torque demands can cause oscillations around the required operating point therefore the next improvements of this method are focused on the reduction of the oscillation impact [3]. Advantage of the method is that it needs not to operate in the unstable part of the characteristic to achieve maximum value of the tractive effort.

E. Indirect Methods

Indirect methods are based on another principle than the previous methods. The methods are typically based on detection of dynamic motions. The adhesion-slip velocity characteristic in the linear part provides high damping of some dynamic motions but in the nonlinear part the damping decreases and in the unstable area damping is negative [11]. On this principle a slip control method can be based. The typical dynamic motions are torsional vibrations between wheels on one wheelset [11] or lateral accelerations [12]. Another approach is described in [13] where the described method is based on noise analysis to detect high value of the slip velocity.

F. Hybrid Slip Control Methods

The hybrid slip control methods consist of more slip control methods. The methods run parallel and according some rules the methods are switched. The methods can eliminate some disadvantage of the individual methods. In the hybrid methods combined methods are that reach high efficiency for some parameters range e.g. slip velocity or wheel acceleration. The block diagram of the hybrid slip control method is in Fig. 7.

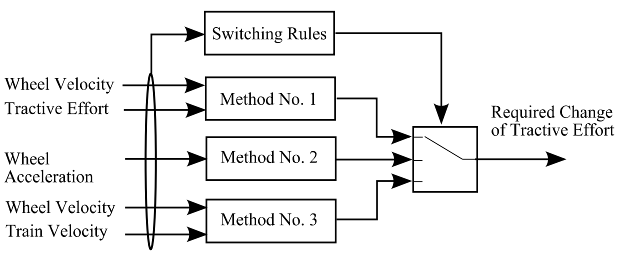

Fig 7. Example of the hybrid slip control method

G. Methods Overview

In Table I there is method overview and the required parameters that can be measured and additional parameters that have to be find out by another method than by measurement or parameters that are preset but are difficult to be determined. In the table there is written name of group of method, measured parameters that can be measured by internal locomotive sensors or calculated by locomotive computer and additional requirements that have to be measured by additional sensors or have to be estimated or parameters that have to be preset during controller set.

TABLE I.
METHODS OVERVIEW

Method name	Measurable Parameters	Additional requirements
Methods based on slip velocity control to a Constant Value	Wheel velocity Train velocity	Threshold velocity
Methods based on searching of maximum value of the adhesion characteristic	Motor torque Motor speed	Estimation of load torque or adhesion coefficient Moment of Inertia
Methods based on speed controller	Wheel velocity Motor torque	Required acceleration
Methods based on characteristic slope determination	Wheel velocity	Required phase shift
Indirect methods	-	Special requirements
Hybrid slip control methods	Depends on combination of methods	Depends on combination of methods

IV. SIMULATION RESULTS

Simulation results are shown for the method that is based on speed controller that is described in the previous part in detail. The method was simulated by Matlab/Simulink. The results of simulation are shown in Fig. 8.

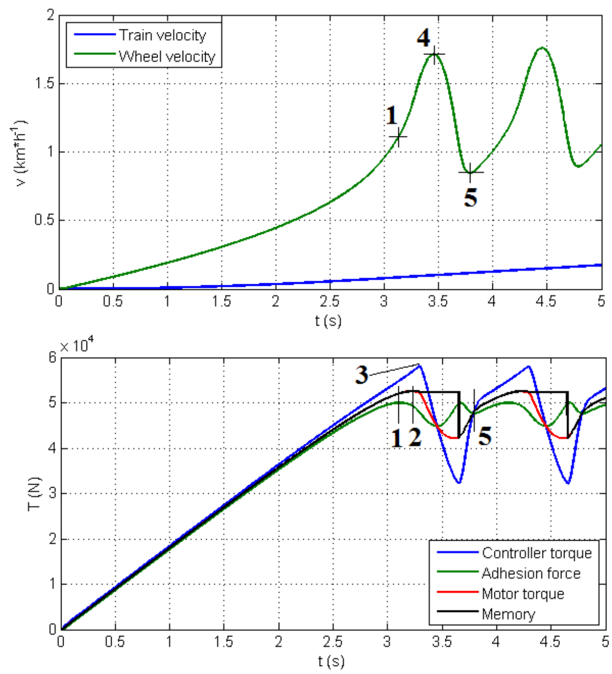

Fig .8. Simulation results of the method based on speed controller.

Required motor torque increases from zero to value that is above maximum adhesion force. The force is not shown in Fig. 8 but the time course is similar to controller torque. When value of a tangential force increases above an adhesion force (point 1 in Fig. 8) the wheel velocity rapidly increases. The slip velocity is approximately $1\ km{\cdot}h^{-1}$ and the maximum value of the adhesion coefficient is 0.35. Train velocity constantly increases. When the peak of the adhesion-slip velocity characteristic is achieved the motor torque starts decreasing and its maximum value is stored in memory (point 2). The difference between the maximum value of the adhesion force (point 1) and motor torque (point 2) is moment of inertia of the electric drive and wheelset. After detecting maximum value of the adhesion-slip velocity characteristic the required torque is decreased (point 3) and the wheel velocity starts decreasing too. The delay between maximum detecting and controller react is caused by controller set. Return of the operating point to the stable area of the characteristics is detected by increasing the motor torque and in this time the controller torque is increased to achieve the required torque (point 5). Because the required value of the tangential force is greater than an adhesion force the process is repeated and some acts of a train driver or some master controller is necessary to avoid next slip.

During simulation an operating point of tangential force to the adhesion force on the adhesion-slip velocity characteristic was tracked.

The result is shown in Fig. 9. In the Fig. 9 it is shown an adhesion force and the motor torque recalculated to tangential force. Points 1, 4 and 5 correspond to points 1, 4 and 5 from Fig. 8. In Fig. 9 it is shown that the tangential force starts increasing above the adhesion force before the characteristic maximum value. Return to the stable area is possible when the tangential force is decreased below the adhesion force (point 4) then the operating point returns to the stable area. Arrows in Fig. 9 shows the operating point moving. An area that is defined by red curve can be reduced by a controller setting. Note the adhesion force returns back to the same characteristic. According [3] the return characteristic for the adhesion force a slightly different way has to be. The same return way is caused by the simpler adhesion characteristic model. But the simplification has no effect to the slip control simulation.

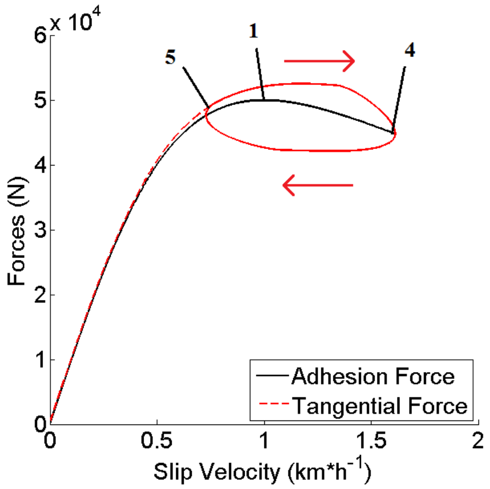

Fig .9. Simulation results of the operating point trajectory

V. CONCLUSION

Some slip control methods that are used in locomotives are presented in the paper. The methods are designed to achieve the maximum tractive effort if it is required. The described methods are divided according principle of their operations into six groups. Methods in the first group are older methods that are based on the slip velocity determination that is difficult to measure therefore the methods very often uses the relative slip velocity. Methods in the second group determine maximum on an adhesion-slip velocity characteristic. The advantage is that the methods need not to determine the slip velocity but the methods oscillate around the operating point. When the oscillations are in the unstable area of the characteristic motor torque can significantly fluctuate. Method in the third group uses a speed controller to control the slip velocity to an appropriate value. The method can operate in any part of the adhesion-slip velocity characteristic but the method needs fast control loops and causes large changes of the tractive effort. Fourth group of methods determines the slope of the characteristic and the method needs not operate in the unstable area of the characteristic but the method causes motor torque fluctuation in principle. In the fifth group there are described indirect methods that are based on locomotive dynamic motions that changes with position of the operating point on the characteristic. In the last group there are described hybrid slip control methods using more slip control methods to improve the controller properties. The method that is based on the speed controller was chosen for simulation. The method was improved against the original method. The method was chosen because the method could be implemented in a locomotive.

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