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— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

[Continued on next page]

(54) **Title**: METHOD AND APPARATUS FOR TORQUE CONTROL OF AN ELECTRICAL MACHINE

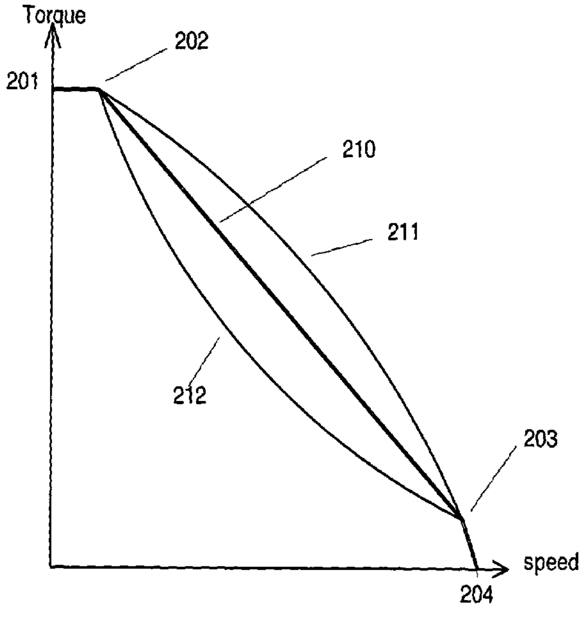

Figure 2

(57) **Abstract**: A control system for an electrical machine drive system which actively controls the machine excitation during conditions of rapid acceleration or deceleration to bring the machine to rest at the point when a specified torque or force has been applied to a mechanical load. This is achieved without requiring any load torque transducer and automatically compensates for inertial energy in an active manner so that when the electrical machine comes to rest the load which has been applied is close to the specified value, irrespective of the rate of change of speed which has occurred. The system comprises an electrical machine, a mechanical drive mechanism connected between the output of the electrical machine and the load, a circuit to supply current to one or more of the windings of the electrical machine, the torque controller having a function of expected load torque variation with electrical machine speed and involving the steps of monitoring the electrical machine speed to calculate rate of change of speed; estimating inertial torque of the electrical machine system; estimating the electrical machine torque from measurements of currents and/or voltages; estimating load torque; calculating a load torque error between the estimated load torque and expected load torque obtained from the function of expected load torque variation evaluated at the instantaneous electrical machine speed and using the load torque error to increase or decrease the electrical machine torque.

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Method and Apparatus for Torque Control of an Electrical Machine

Technical Field

This invention relates to the control of an electrical machine to deliver a specified torque to a load in which the speed is changing rapidly without the need for a torque sensor.

Background

An electric machine is often used to apply a torque to a mechanical load, often through a gear train. In steady state systems the torque applied to the load can be estimated from the electrical machine torque. In most electrical machines the machine torque (electromagnetic torque) is a known function of the current flowing in the phase windings or field and armature windings of the machine. Usually the machine torque will be proportional to machine current or to machine current squared. In alternating current motors and electronically commutated motors, the instantaneous current in the phase windings is changing as the rotor rotates but its effective value in a rotating reference frame can be related to the torque output of the motor.

However, in cases where motor speed is changing rapidly the torque produced by a motor is not an accurate estimation of the load torque. The actual load torque becomes a complex combination of motor electromagnetic torque, dynamics of the mechanical load and the inertia of the drive-train. In addition if the machine is connected to a gearbox or belt drive and then to the load, there will be further dynamic effects making it very difficult to control the torque applied to the load. This is a significant problem if the load has low inertia compared to the electrical machine.

An example of an application where this is important is an electric torque tool used to tighten a bolt to a specified torque. As the bolt tightens, the torque seen by the motor rises rapidly, causing the motor to decelerate at a very high rate. Under such circumstances the motor inertia and the inertia of the drive train will cause the load torque to be significantly in excess of the electromagnetic torque estimated from the motor current. A further example of such an occurrence would be in an electromechanical braking system where a motor drives a brake shoe into contact with a rotating drum or disc and is required to achieve a specified contact force to deliver a specified braking torque on a wheel. The kinetic (inertial) energy associated with the spinning motor and drive-train will cause the torque to overshoot the required torque set point and lead to an excess of braking force on the wheel.

Compensation for the inertial overshoot is possible in a closed system where the rate of change of load torque can be accurately predicted or observed. Prior art systems to compensate the required motor torque have used learning techniques such as disclosed in US 5315501 which reduced the torque setting on the motor by an amount calculated from previous deceleration times. This system works well providing there are no external changes on the systems each time the motor runs. In order to incorporate some feedback on the rate of rise of torque US 4210852 discloses a method of shutting down the motor when the current reaches a particular value and reduces the current threshold further in proportion to the rate of change of current. The implementation of US 4210852 still requires a motor of low inertia since at low output torques the shutdown trigger point may occur while the motor is at high rotational speeds. Furthermore, the trigger to shutdown the motor may be falsely triggered due to some mechanical imperfections in the drive train causing a temporary rate of change of current. Finally such schemes are wholly inadequate if the rate of rise of torque seen by the motor is non-linear.

Summary

It is the purpose of this invention to disclose a control system for an electrical machine drive system which actively controls the machine excitation to bring the machine to rest at the point when a specified torque or force has been applied to a mechanical load.

This can be achieved without requiring any load transducer overcoming the limitations of the prior art and automatically compensating for inertial energy in an active manner so that when the electrical machine comes to rest the load which has been applied is close to the specified value, irrespective of the rate of change of speed which has occurred.

According to one aspect of the present invention, a torque controller for an electrical machine system is provided, the system comprising an electrical machine, a mechanical drive mechanism connected between the output of the electrical machine and the load, a circuit configured to adjust current in one or more of the windings of the electrical machine, the torque controller configured to have a function of expected load torque variation with electrical machine speed and incorporating the steps of monitoring the electrical machine speed to calculate rate of change of speed; estimating inertial torque of the electrical machine system; estimating the electrical machine torque from measurements of currents and/or voltages; estimating load torque; calculating a load torque error between the estimated load torque and expected load torque obtained from the function of expected load torque variation evaluated at the instantaneous electrical machine speed and using the load torque error to increase or decrease the electrical machine torque.

The function of expected load torque variation with electrical machine speed has at least two specified points, the first specified point being related to the electrical machine torque under stall conditions which if applied to the mechanical drive mechanism would deliver a required final value of load torque or force and the second specified point related to a required no load speed for the electrical machine.

The function of expected load torque variation with electrical machine speed follows linear relationships between the at least two specified points so that the expected load torque can be calculated at all electrical machine speeds.

In a further aspect of the invention the function of expected load torque variation with electrical machine speed follows at least one non-linear relationship between the at least two specified points so that the expected load torque can be calculated at all electrical machine speeds.

According to the invention the electrical machine torque is reduced under conditions of rapid deceleration.

According to the invention, the torque controller acts to make the electrical machine torque negative under conditions of rapid deceleration such that mechanical energy is converted into electrical energy, further increasing the deceleration of the electrical machine system.

In a further aspect of the invention the torque controller is used to control an electrical machine system in a torque tool.

In a further aspect of the invention the torque controller is used to control an electrical machine system in an electromechanical braking system.

Brief description of the drawings

The invention will now be described with reference to the following diagrams in which :

Figure 1 shows the torque versus time for two different types of load;

Figure 2 shows an example of a function of expected load torque variation profile;

Figure 3 shows a block diagram of a motor, load and electronic controller.

Description

This invention has particular application when an electrical machine is used to apply an increasing load to a mechanical system. One application is an electrically driven torque tool designed to tighten a nut and bolt assembly, thus applying an increasing compressive force on surfaces being bolted together. As the angle turned by a nut relative to a bolt increases the pitch of the thread increases the forces on the surfaces being compressed. As a result the torque on the electrical machine increases causing the electrical machine to slow down to a stop.

A similar characteristic occurs in an electromechanical brake actuator or clutch assembly where an electrical machine is used with a gear mechanism to apply an axial or radial force between one or more brake shoes and a disc or cylinder to create a braking torque. Such systems can be used in the mechanical brakes in a wheel for a vehicle.

In such applications it is desirable to control the electrical machine to stop when the torque (or compression force), as applied at the point of action of the load, has reached a desired value. Stopping the motor too soon leaves a bolted joint below the specified torque, leading to a possible failure of the mechanism or structure. On the contrary, an over-tightened bolt is dangerous as the increased stress on the components could lead to failure.

In an electromechanical braking system the accurate control of the applied force is crucial, particularly where maximum braking torque on the point of wheel locking is required. Such accurate control would be required, for example, in electro-mechanically actuated anti-lock braking systems.

Whilst the method and apparatus of this invention could be applied to many potential applications the method will be illustrated with specific reference to bolt tightening using an electrically powered torque tool.

In bolt-tightening applications the rate of rise of torque versus angle depends on many factors including the pitch of the screw threads and the types of material being compressed. The angle turned by the nut relative to the bolt to achieve the desired torque setting may be a few degrees or may be many revolutions. This leads to a very wide range of bolted joints and an electric motor driven torque tool must therefore be able to estimate the torque on the bolt and stop the motor when the torque or compressive force has reached the correct level. Ideally an electric motor driven torque tool should be able to estimate the joint rate or type of a joint during the joint to ensure that the motor is stopped at the right point on completion without taking excessive time for each joint. A soft joint may typically require rotation of 360° or more of the nut relative to the bolt for the torque to increase from 10% to 100% of the specified value. In contrast a hard joint could achieve the same increase in torque with the nut turning only 30° relative to the bolt. In a hard joint the time taken for the torque to rise from 10% to 100% will be less than 1 second and will typically be in the region of 100 ms to 500 ms.

Since the torque of a bolted joint rises with angle turned by the thread and, as the motor speed will initially be high prior to the onset of the increasing torque, the initial rate of rise of torque with time will be very high, due to the high rotational speed of the motor. As the torque on the motor shaft increases, the motor will slow down, and the rate of rise of torque with time decreases as the joint progresses. Figure 1 shows a plot of load torque versus time during the completion of two types of bolted joints. Curve 11 shows the torque initially rising rapidly with time while the motor speed is high (angle turned per unit time is large). As the motor speed decreases the rate of rise of torque decreases until reaching the stall torque, 13. Curve 12 shows a slower rate of rise of torque. This is typical of a type of joint requiring a much higher angular rotation to achieve high compressive forces. In this joint the pitch of the thread of the nut may be shorter or the materials more compressible. Curve 12 still exhibits the same characteristic drop in the rate of rise of the torque as the joint progresses due to the slower speed of the motor. The two types of joint will be referred to as hard (fast rate of rise of torque with joint angle) and soft (slow rate of rise of torque with joint angle). The time taken to complete the two types of bolted joint is quite different but the shape of the curves (decreasing gradient with time) are similar.

The particular problem addressed by this method is that the in the 'hard' joint type there is a greater tendency for the joint to be over-tightened due to the additional kinetic energy associated with the inertia of the motor and gear system. The kinetic energy associated with the rotating parts of the system causes additional torque to be applied to the joint during deceleration and after the motor is switched off. A motor controller according to this invention can detect the type of the joint and use simple calculations to adjust the motor torque demand so that the motor can be stopped rapidly (hard joint) or continue to deliver torque (soft joint). The innovation over the prior art is that the calculations are simple enough to be implemented in real time as the joint torque increases so that any excess inertial energy is removed while the motor is spinning and before the controller switches off.

The motor will usually be turning at or near to a free-run speed while a nut is loose on a bolt or the nut is running down the threads before meeting the surfaces to be compressed. As soon as the nut comes into contact with the surfaces to be compressed, the torque will begin to rise and the motor speed will start to drop. The natural torque speed curve of an electric motor is such that as the motor speed drops the current will increase to meet the higher torque requirement of the load. Prior-art controlled systems would also act to increase the torque of the motor to deliver the increased torque required by the load.

As the motor slows down to deliver more torque, the joint rate can be estimated from combined effects of the motor torque and the rate of change of motor speed. The rate of change of motor speed is negative indicating a deceleration. Higher deceleration rates are indicative of faster joint rates or harder joints.

Despite the wide variation of joint types or load types which a torque tool may encounter, it is possible to produce a function of expected load torque variation with electrical machine speed. This function can be substantially independent of the joint type. The function is used in a dynamic torque controller to determine the instantaneous torque requirement of the electrical machine.

Figure 2 shows an example of a function of expected load torque variation with electrical machine speed. The function of expected load torque variation will have at least two specified points. In the function illustrated by Figure 2 there are four specified points shown. Point 201, is the required stall torque, T_1, which would deliver the specified load torque through the appropriate gearing mechanism. This point 201 is associated with zero motor speed. Point 202 occurs at speed ω_1 and motor torque, T_1, and is the motor speed where the motor would be switched off having completed the joint to the final torque value. Point 203 occurs at speed ω_2 and motor torque, T_2, and is the motor speed desired when there is no external load on the drive system. The torque T_2 is therefore known as the no load torque on the motor and ω_2 is the no load speed of the motor. Point 204 extends the first function to meet the x-axis at or just above the required no-load speed.

Since the points 201 and 202 are closely related to the required final torque value of the load and points 203 and 204 are closely related to the no-load speed of the motor (and hence the load mechanism), it can be seen that the shape of the function of expected load torque variation (or motor torque variation when all the values are referred to the motor shaft) is determined principally by two points and their associated values, final load torque and no load speed.

The line joining Point 202 and Point 203 on the function can be linear as shown by line 210 in Figure 2 or could be curved, either concave (line 212) or convex (line 211) or may be S-shaped, following a path between 211 and 212. The shape of this function which is most suited to a particular application will depend on the characteristic of the load and the available power from the motor. A convex shape will require a motor of greater power and a concave shape is more closely related to constant motor power characteristic. The function in Figure 2 has been described with the load torque and speed values converted to motor torque and speed values by referring the values across the gearbox. The function can also be used with output torque and speed values.

As user requirements change such as stopping torque value, the points 201, 202, 203 and 204 and the path of the function of expected load torque can be recalculated prior to starting the motor or may even be recalculated while the motor is running. In some applications only the final load torque value needs to be changed by the user controlling the application. The no load speed would usually be pre-determined and may be limited by other constraints such as available voltage. Alternatively the no-load speed may be related to the final stall torque value and could be reduced as the stall torque value is reduced. This will further reduces the chances of overshooting the final torque value when the final torque value is reduced.

Unlike prior-art methods, the function of the expected load torque is not the torque versus speed profile for the motor. This function is the expected torque vs speed profile for the torque (or force) seen at the output shaft referred back through the gearbox. This function is therefore representative of a target load torque profile. This profile can be pre-calculated and stored in memory within the machine controller or can be calculated from stored parameters or parameters set by the user. It does not need to be changed for different joint types. In an automotive braking application it does not necessarily need to be altered as brake surfaces wear out and the travel distances increase. However, in a braking system where it is known that as the brake surfaces wear, the travel distance increases, it would be possible to adjust the characteristic to compensate for wear.

The function of expected target load torque is used in a dynamic torque calculator to control the dynamic motor torque required. The torque calculator follows the following steps :

(i) Monitor or estimate the current flowing in the motor windings and using a suitable motor model, predict the electromechanical shaft torque of the motor;

(ii) Monitor the motor speed and calculate acceleration (or deceleration) (when present);

(iii) The inertial torque of the drive-train is obtained by multiplication of a known value of inertia of the motor shaft and mechanical drive-train times the acceleration (or deceleration) estimate;

(iv) The inertial torque (iii) and electromechanical shaft torque (i) are combined to create a load torque estimate (referred to motor shaft);

(v) The load torque estimate is then compared with the function of expected load torque evaluated at the present shaft speed and a load torque error calculated. If the load torque estimate is greater than the value of the function of expected load torque at the present rotational speed, the torque error indicates that the motor torque should be reduced to avoid exceeding the final stopping torque. If the load torque estimate is less than the value of the function of expected load torque at the present rotational speed, the torque error indicates that the motor torque can be increased without significant risk of exceeding the final stopping torque.

(vi) Control of motor torque can be achieved by lowering the current in the windings of the motor (lowering the voltage) and/or adjusting the angle of the stator magnetic field with respect to the rotor position (electronically controlled motors). It is possible that the torque error is such that it is necessary to make the motor torque negative. In this case the motor becomes a generator extracting mechanical energy from the rotating system.

The method can be applied by repeating the above steps one or more times during the deceleration of the motor. It is advantageous to repeat the above steps repetitively throughout the entire motor operation including acceleration, no-load running and deceleration.

It is also possible to use the torque error in a dynamic motor torque controller, where the torque error is used with integral and proportional gains (referred to as a PI controller). The output of such a controller is the actual torque requirement of the motor (or generator when torque required is negative).

When the torque demand on the motor becomes negative, the motor needs to apply a braking torque to produce a faster deceleration. This braking torque can be applied by turning the motor into a generator and converting mechanical inertial energy (kinetic energy) into electrical energy. The motor controller needs to be designed to store this energy, usually in a capacitor or battery. During the highest deceleration the motor torque may become negative. This illustrates the innovative feature disclosed herein. Prior-art motor controllers would tend to apply the greatest positive torque during times of fast deceleration to try to counteract the rapid rise in load torque. Application of thinvention method disclosed herein creates the opposite effect to prior art motor torque control systems.

Control of an electrical machine drive system as disclosed herein is unusual in that it operates against the accepted prior art methods of torque control and is unstable. The machine controller disclosed herein reduces the torque demand in the electrical machine when machine deceleration is detected. Prior art torque controllers would detect a drop in speed and increase the torque demand to counteract the drop in speed. Control of an electrical machine therefore includes a torque calculator which lowers machine torque during periods of rapid deceleration, inducing even greater levels of deceleration.

Figure 3 shows a block diagram of a motor, load and electronic controller. A supply voltage, 100, which may be derived from a battery or a mains ac supply is provided to an electronic motor controller, 101. The electronic motor controller 101 also receives a torque demand signal 102. The electronic motor controller supplies voltage and current to the motor 103 which is connected to the load 104. The connection between the motor 103 and the load 104 will often require a mechanical gear ratio, or other form of mechanical drive such as a belt and pulley, rack and pinion or ball screw. The electronic motor controller will have a means to calculate or measure the motor speed. This may be a back emf measurement of a dc motor or in the case of a brushless motor it will be related to the electronic commutation frequency. The electronic commutation frequency can be derived from an encoder on the motor shaft or may be derived from sensorless control methods, calculated from the motor voltages and currents. The electronic motor controller therefore implements the torque estimation and torque control as disclosed herein.

In most electric motors the current in the windings can be directly related to the torque output of the motor shaft. Application of the invention can therefore be achieved without requiring a torque sensor by using the electronic motor controller to monitor and control the current in the motor windings to deliver the required load torque.

The methods and apparatuses disclosed herein can be used with all types of brushed or brushless motor. They are particularly advantageous when coupled with a brushless electronically controlled motor is. Firstly, brushless motors can be designed to have low inertia, which reduces the inertial energy which has to be compensated for. Secondly, brushless motors require a power electronic circuit to monitor the rotational position of the rotor and the power electronic circuit can be configured to vary the currents in the windings of the electrical machine to increase or decrease the torque of the motor. Such systems can also adjust the current to make the torque negative such that the motor becomes a generator and the torque acts to reduce the rotational speed of the motor. The controller of such a motor also has easy access to the instantaneous rotational speed of the rotor to calculate the acceleration and hence the required motor torque in real time.

The methods and apparatuses disclosed herein can be used with brushless permanent magnet motors or with reluctance motors such as switched reluctance, synchronous reluctance or flux switching motors.

Another purpose of an electric torque tool is to re-tighten or check the torque of a joint which has already been tightened. In this case deceleration of the motor will occur soon after starting and the methods and apparatuses disclosed herein can be implemented automatically since the deceleration will result in a rapid rise in torque estimate and will trigger a reduction in the required motor torque to ensure that if the joint is already tightened to the specified torque then it will not be over-tightened.

Application of the methods and apparatuses disclosed herein to an electromechanical braking system in a vehicle or aircraft can also ensure that brake forces can be applied to a wheel or other rotating system with the highest response rate while ensuring that the required force is not exceeded. The system is automatically adaptive to changes in the braking system through wear of the friction surfaces.

CLAIMS :

1. A torque controller for an electrical machine system, the system comprising an electrical machine, a mechanical drive mechanism connected between the output of the electrical machine and the load, a circuit configured to adjust the current in one or more of the windings of the electrical machine, the torque controller configured to have a function of expected load torque variation with electrical machine speed and incorporating the steps of monitoring the electrical machine speed to calculate rate of change of speed; estimating inertial torque of the electrical machine system; estimating the electrical machine torque from measurements of currents and/or voltages; estimating load torque; calculating a load torque error between the estimated load torque and expected load torque obtained from the function of expected load torque variation evaluated at the instantaneous electrical machine speed and using the load torque error to increase or decrease the electrical machine torque.

2. A torque controller of claim 1 wherein the function of expected load torque variation with electrical machine speed has at least two specified points, the first specified point being related to the electrical machine torque under stall conditions which if applied to the mechanical drive mechanism would deliver a required final value of load torque or force and the second specified point related to a required no load speed for the electrical machine.

3. A torque controller of claim 1 or 2 wherein the function of expected load torque variation with electrical machine speed follows linear relationships between the at least two specified points so that the expected load torque can be calculated at all electrical machine speeds.

4. A torque controller of claim 1 or 2 wherein the function of expected load torque variation with electrical machine speed follows at least one non-linear relationship between the at least two specified points so that the expected load torque can be calculated at all electrical machine speeds.

5. A torque controller of any preceding claim wherein the electrical machine torque is reduced under conditions of rapid deceleration.

6. A torque controller of any preceding claim wherein the controller acts to make the electrical machine torque negative under conditions of rapid deceleration such that mechanical

energy is converted into electrical energy, further increasing the deceleration of the electrical machine system.

7. A torque controller of any of claims 1-4 wherein the controller acts to increase electrical machine torque under conditions of slow deceleration such that the electrical machine system does not stall.

8. A torque tool incorporating a torque controller for an electrical machine system according to any preceding claim.

9. A torque tool according to claim 8 wherein the first specified point of the function of expected load variation is adjustable and the second specified point is adjustable.

10. An electromechanical brake incorporating a torque controller for an electrical machine system according to claims 1-7.

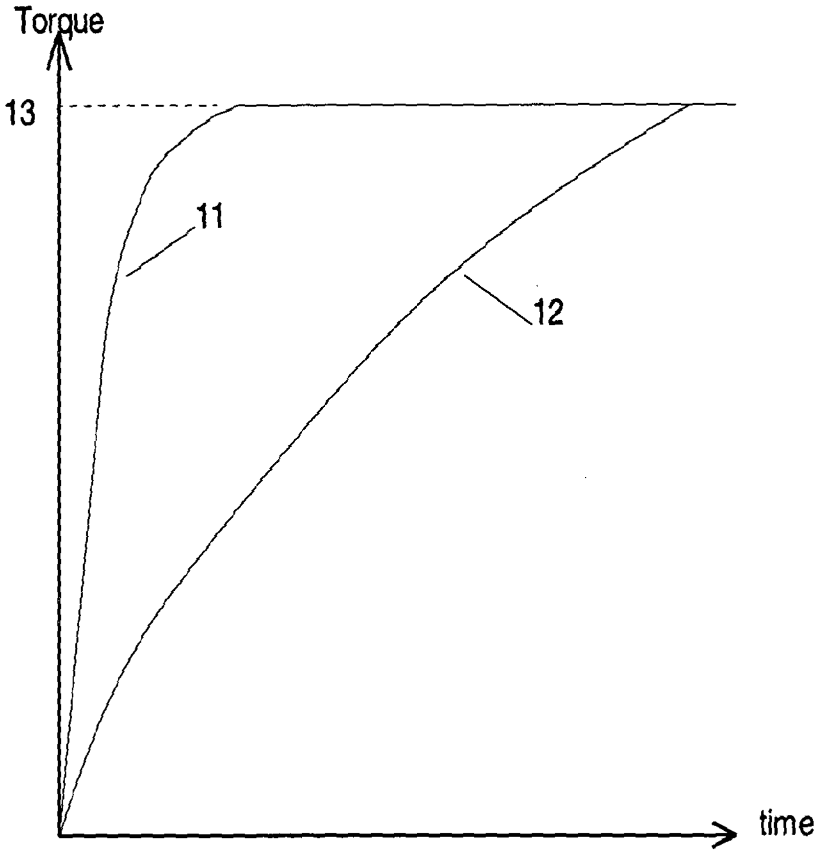

Figure 1

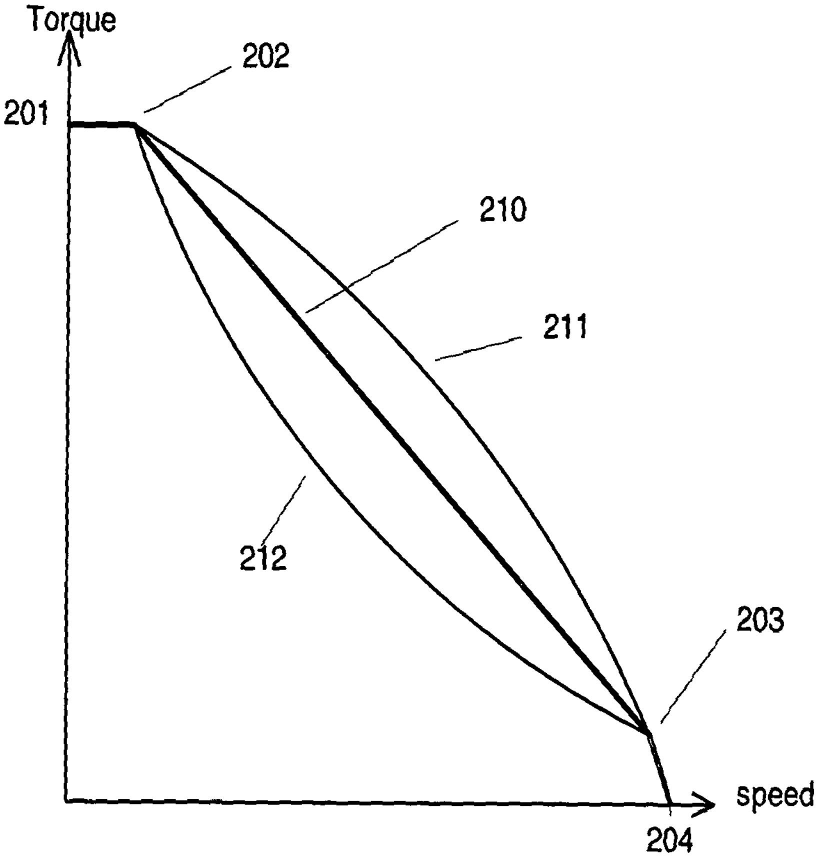

Figure 2

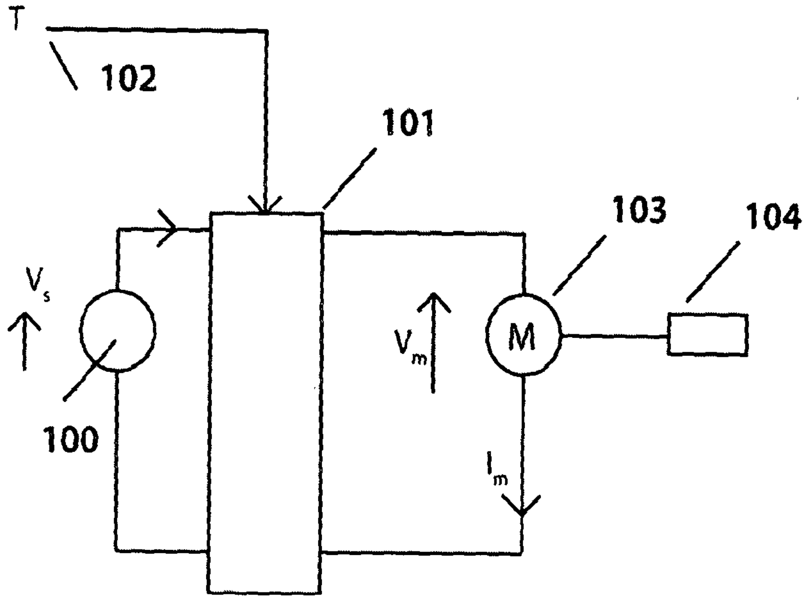

Figure 3