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on basis of the measured temperature in step e) and the stored resistance curve of the ECU (15); g) Subtracting the resistance of the ECU (R_{ECU}) from the determined power pack resistance ($R_{\text{powerpack}}$); h) Determining the temperature of the motor coils ($T_{\text{motorcoil}}$) based on the value obtained in step g) and the stored resistance curve of the motor coils (14); i) and Obtaining the lost temperature increment ($T_{\text{LostIncrement}}$) by subtracting the measured temperature of the ECU (T_{ECU}) from the determined temperature of the motor coils ($T_{\text{motorcoil}}$).

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Coil temperature estimation

15 The present invention relates to an electric power assisted steering system of a motor vehicle according to the preamble of claim 1.

Electric power assisted steering system of a motor vehicle are provided with an electric motor that provides an assist power to a turning operation of a steering handle. An electric power steering unit is used to prevent the motor or an electronic control unit (ECU) carrying out a driving control of this motor which overheats the motor and/or causes permanent damage by limiting a current flowing through the motor.

Generally to prevent the motor from being overheated the motor coil temperature is estimated. Generally, the estimated coil temperature is calculated as follows: a base temperature is measured, which is the module or board temperature of the ECU and which is detected by a thermal sensor in the ECU, then a heat increment $T_{Increment}$, which is caused by the dissipated power of motor, is added to the base temperature. In a system restart the incremented heat $T_{Increment}$ gets lost. In order to estimate the correct coil temperature, the estimator has to start from the base temperature again,

$$T_{CoilEstimated} = T_{Increment} + T_{ECU} \xrightarrow{\text{System Restart}} T_{CoilEstimated} = 0 + T_{ECU} = T_{ECU} \xrightarrow{\text{Problem}} T_{ECU} \ll T_{CoilReal}$$

During the rebuild of the heat increment the motor is unprotected from

overheating. The lost heat increment can be higher than 100°C. After some time the estimator will reach the correct estimated coil temperature, but this might take several minutes up to one hour.

5 Until the estimated temperature is close to the real temperature of the motor, the motor is not protected from being overheated, which can cause permanent damages and demagnetization of the motor. An inaccurate temperature signal can further cause a failure in diagnostics.

10 US 2005/0269150 A1 discloses a method how to reduce the load on a battery and improve the starting characteristic of a motor when the ignition switch is changed into OFF state. If an ignition switch changes from OFF state to ON state, an initial value of the current limit value needs to be set and an overheat protection is guaranteed. Therefore, the last state of the controller (before the ignition switch is changed from ON to OFF state) and a process state during the OFF state are stored. However the measurement of the
15 temperature is not precise enough, because it takes into account the motor temperature and not the temperature of the coils.

US 8,972,115 B1 discloses a method for an overheat protection of a power pack entering a failsafe mode, wherein the motor current can be limited. A motor temperature is estimated using thermal resistance and the motor
20 current. The thermal resistance is calculated using the vehicle speed and the power pack temperature. This calculation is not precisely enough, because it takes into account the complete power pack temperature and not the motor coil temperature.

25 It is an object of the invention to provide an electric power assisted steering system of a motor vehicle with improved estimation of motor temperature to prevent the electric motor from overheating and to provide more accurate and robust diagnostics.

This problem is solved by a method for estimation of lost temperature increment after system restart for motor coil temperature estimation in an
30 electric power assisted steering system of a motor vehicle with the features listed in claim 1. Further advantageous embodiments can be taken from the

dependent claims.

Accordingly, a method for estimation of lost temperature increment in an electric power steering apparatus of a motor vehicle with a power pack comprising an ECU with a temperature sensor and an electric motor, is

5 provided, said method comprises the steps of:

- a) Storing a given resistance curve of the motor coils ;
- b) Storing a measured resistance curve of the ECU ;
- c) Measuring a demand voltage vector, a current feedback value $I_{d,fb}$ based
on a demand current vector and a battery voltage during a special
10 measurement pulse;
- d) Determining a power pack resistance based on the parameters
measured in step c);
- e) Measuring the temperature of the ECU with the temperature sensor;
- f) Determining the resistance of the ECU on basis of the measured
15 temperature in step e) and the stored resistance curve of the ECU;
- g) Subtracting the resistance of the ECU from the determined power pack
resistance;
- h) Determining the temperature of the motor coils based on the value
obtained in step g) and the stored resistance curve of the motor coils;
20 and
- i) Obtaining the lost temperature increment by subtracting the measured
temperature of the ECU from the determined temperature of the motor
coils.

Preferably, the motor coil resistance curve is given by

$$25 \quad T_{motorcoil} = \frac{\left(\frac{R_{motorcoil}}{R_0} \right)^{-1}}{\alpha_{Cu}} + T_0, \text{ wherein } T_{motorcoil} \text{ is the motor coil temperature,}$$

$R_{\text{motorcoil}}$ the resistance of the coil, T_0 the room temperature, α_{Cu} the heat coefficient of the coils' copper and R_0 the resistance of the coil at room temperature.

5 In one embodiment, the motor coil resistance increases with about 39%/100°C.

It is advantageous that the special measurement pulse is so short, that the rotor of the motor does not move. Preferably, the special measurement pulse is less than 25 ms. The motion of the rotor and therefore the motor torque generation is further prevented by using the direction of a demand current
10 vector $I_{d,d}$ and direction of a demand voltage vector $U_{d,d}$.

In a preferred embodiment, the motor coil resistance curve and the measured ECU resistance curve are stored by polynomial equations in the ECU software. The resistance curves can be further stored in look-up tables. In a preferred embodiment the proper polynomial equation can be selected. Favourably, the
15 motor coil resistance curve and the ECU resistance curve are stored each by two polynomial equations, one for a first and one for a second part, wherein the first and second part are separated by the minimum of resistance of ECU resistance curve.

A preferred embodiment of the present invention will be described with
20 reference to the drawings. In all figures the same reference signs denote the same components or functionally similar components.

Figure 1 shows a schematic illustration of an electric power steering apparatus;

Figure 2 is a block diagram showing an electrical structure of the electric
25 power steering apparatus; and

Figure 3 shows the calculated resistances plotted against temperature.

Figure 1 is a schematic diagram of an electric power steering apparatus 1. A steering wheel 2 is fixed to a steering shaft 3, and the steering shaft 3 is coupled to a rack 4 via a rack-and-pinion mechanism 5. Rotation of the

steering shaft 3 accompanying a steering operation is converted into a reciprocating linear motion of the toothed rack 4 by the rack-and-pinion mechanism 5. The linear motion of the rack 4 changes the steering angle of the steered wheels 6. To provide steering assistance, an electric motor 7
 5 mounted to the side of the rack housing drives a ball-screw mechanism 8 via a toothed rubber belt 9.

Electric power assist is provided through a steering controller (ECU) 10 and a power assist actuator 11 comprising the electric motor 7 and a motor controller 12. The steering controller 10 receives signals representative of the
 10 vehicle velocity v and the torque T_{TS} applied to the steering wheel 2 by the vehicle operator. In response to the vehicle velocity v and the operator torque T_{TS} , the controller 10 determines the target motor torque T_d and provides the signal through to the motor controller 12, where the duty cycles are calculated to produce the phase currents via PWM (pulse-width modulation). The
 15 steering controller 10 including a temperature sensor 16 and the electric motor 7 forms a unit referred to as power pack 100. The power pack 100 can comprise further elements like the motor controller 12 or sensing circuits for sensing currents and/or voltages. The power pack 100 is fed with battery voltage U_{bat} .

Figure 2 shows a block diagram of the electrical structure of the electric power steering apparatus 1. The steering controller 10 receives signals
 20 representative of the vehicle velocity v , the torque T_{TS} applied to the steering wheel 2 by the vehicle operator and a base temperature T_0 and derives the target motor torque T_d . This torque is fed to the motor controller 12 which
 25 determines the voltage input for the PWM and a motor driver 17 generates via the PWM the motor currents $I_{coils} = i_U, i_V, i_W$. Hence, the motor 7 generates a torque T which compensates the operator torque T_{TS} .

An estimator estimates the temperature of the motor coils to adjust if
 necessary the current flowing through the motor 7 in order to prevent damage
 30 of the motor 7. A temperature sensor 16 measures the temperature T_{ECU} of the ECU 10. The estimator adds to the measured temperature of the ECU T_{ECU} a heat increment $T_{Increment}$.

$$T_{CoilEstimated} = T_{Increment} + T_{ECU}.$$

The heat increment is derived as follows

$$T_{Increment} = T_{IncrementPrev} + \left\{ \left(\frac{T_s}{C_{Thermal}} \right) \cdot (P - (T_{IncrementPrev} \cdot G_{Thermal})) \right\},$$

wherein $T_{Increment}$ is the value of temperature increment to thermal ground in the actual control cycle, $T_{IncrementPrev}$ is the value of temperature increment calculated in the previous running cycle, $T_s = 1/f_s$ with f_s the running frequency of the estimator, P is the value of calculated dissipated power of motor in the actual control cycle, $G_{Thermal}$ is the thermal conductance and $C_{Thermal}$ is the thermal capacity.

- 10 After restart of the system the lost heat increment $T_{LostIncrement}$ needs to be recovered. This is done with the following method. Figure 3 shows schematically the resistance curves of the motor coils 14, the ECU 15 and the power pack 13 and the calculation of the motor coil temperature $T_{motorcoil}$.

- Before operation of the estimator the resistance of the power pack $R_{powerpack}$ 13 at different temperatures over the relevant range is measured. The power pack resistance curve 13 has a turning-point, separating the curve into a cold and warm part, wherein the turning point can be in a range between 0°C and 15°C. This turning point is the minimum of the resistance curve of the capacitor. The shape of the resistance curve is representing the different temperature dependencies of the materials and electrical parts of the ECU 10. A polynomial formula for each part of the power pack resistance curve 13 is determined based on the demand voltage vector $U_{d,d}$ and the demand current vector $I_{d,d}$ expressed in a coordinate system fixed to the electrical angular frequency φ of the rotating rotor. The electrical angular frequency φ of the rotating rotor has the same or the opposite direction as the rotor, so the generation of motor torque can be prevented. By using the demand current vector $I_{d,d}$ and the demand voltage vector $U_{d,d}$ self-steering can be prevented.

Further the connection between the motor coil resistance and the temperature of the motor coils, given by

$$T_{motorcoil} = \frac{\left(\frac{R_{motorcoil}}{R_0}\right) - 1}{\alpha_{Cu}} + T_0, \text{ is stored,}$$

wherein T_0 is the temperature of the motor coils at the room temperature.

The resistance of the coil $R_{motorcoil}$ is temperature dependent. The formula depends on the heat coefficient of the coils' copper α_{Cu} . Its value is 39 %

5 /100°C. Next the difference between the two curves 13, 14 is calculated resulting in the ECU resistance curve 15. This curve is stored in the parameter file by the help of two polynomial equations, one for the warm part and one for the cold part, wherein the proper polynomial equation can be selected.

During operation of the estimator and after restart of the system the lost
10 increment $T_{LostIncrement}$ is estimated with the following method;

At first the resistance of the power pack $R_{powerpack}$ is measured. For that a special measurement pulse is used. The duration of this special measurement pulse is less than 25 ms. During this short time the rotor does not move, no steering assist is provided and the driver will not detect any unusual
15 phenomena, like self-steering of the system. When the power pack 100 is started, the power pack resistance $R_{powerpack}$ is calculated by measurement of the demand voltage value $U_{d,d}$ and a current feedback value $I_{d,fb} = I_{Powerpack}$ is determined which flows into the powerpack based on the the demand current value $I_{d,d}$ and the battery voltage U_{bat} and calculation of the voltage drop
20 $U_{powerpack}$ by

$$U_{powerpack} = U_D \cdot \left(\frac{2}{3} \cdot U_{bat}\right)$$

and by

$$R_{powerpack} = \frac{U_{powerpack}}{I_{powerpack}}.$$

A thermal sensor 16, wherein the thermal sensor and the temperature sensor describe the same element, integrated in the ECU 10 measures the temperature of the ECU T_{ECU} . The proper resistance value of the ECU R_{ECU} can then be determined by the measured temperature T_{ECU} and the respective part (cold or warm) of the pre-stored ECU resistance curve. In the next step, the motor coil resistance $R_{motorcoil}$ is determined by subtracting the ECU resistance value R_{ECU} from the resistance of the power pack $R_{powerpack}$. With the use of the stored motor coil resistance curve 14 and the calculated motor coil resistance $R_{motorcoil}$, the motor coil temperature $T_{motorcoil}$ can be calculated. After that the lost heat increment $T_{LostIncrement}$ is determined, which is the difference between the calculated motor coil temperature $T_{motorcoil}$ and the ECU measured temperature T_{ECU} ,

$$T_{LostIncrement} = T_{motorcoil} - T_{ECU}.$$

This way the estimator can be restarted not from the base temperature (T_{ECU}) but with an estimated incremented value $T_{LostIncrement}$.

The estimated motor coil temperature $T_{CoilEstimated}$ is then calculated during system initialization by

$$T_{CoilEstimated} = T_{LostIncrement} + T_{ECU}.$$

After that the estimator proceeds with $T_{Increment}$, whereas in the first calculation cycle $T_{LostIncrement}$ is used as $T_{IncrementPrev}$,

$$T_{CoilEstimated} = T_{Increment} + T_{ECU} \xrightarrow{\text{System Restart}} T_{Increment} = T_{LostIncrement} \Rightarrow T_{CoilEstimated} = T_{LostIncrement} + T_{ECU} \cong T_{CoilReal}$$

Finally right from the start, the electric motor 7 is operated with the correctly estimated motor coil temperature.

The method according to the present invention allows to easily recover the lost heat increment value after restart of the system. Consequently, the estimation of the temperature of the motor coils will start from the correct temperature value. Damage of the motor due to overheat can be prevented. Further a

more robust system diagnostics and a more accurate torque signal estimation can be provided.

Claims

1. Method for estimation of lost temperature increment ($T_{\text{LostIncrement}}$) after
5 system restart for motor coil temperature estimation in an electric power steering apparatus (1) of a motor vehicle with a power pack (100) comprising an ECU (10) with a temperature sensor (16) and an electric motor (7), **characterized in that** said method comprises the steps of:
 - a) Storing a given resistance curve of the motor coils (14);
 - 10 b) Storing a measured resistance curve of the ECU (15),;
 - c) Measuring a demand voltage vector ($U_{d,d}$), a current feedback value $I_{d,fb}$ based on a demand current vector ($I_{d,d}$) and a battery voltage (U_{bat}) during a special measurement pulse;
 - d) Determining the power pack resistance ($R_{\text{powerpack}}$) based on the
15 parameters measured in step c);
 - e) Measuring the temperature of the ECU (T_{ECU}) with the temperature sensor (16);
 - f) Determining the resistance of the ECU (R_{ECU}) on basis of the measured temperature in step e) and the stored resistance curve of the ECU (15);
 - 20 g) Subtracting the resistance of the ECU (R_{ECU}) from the determined power pack resistance ($R_{\text{powerpack}}$);
 - h) Determining the temperature of the motor coils ($T_{\text{motorcoil}}$) based on the value obtained in step g) and the stored resistance curve of the motor coils (14); and
 - 25 i) Obtaining the lost temperature increment ($T_{\text{LostIncrement}}$) by subtracting the measured temperature of the ECU (T_{ECU}) from the determined temperature of the motor coils ($T_{\text{motorcoil}}$).

2. Method according to claim 1, **characterized in that** the motor coil resistance curve (14) is given by

$$T_{\text{motorcoil}} = \frac{\left(\frac{R_{\text{motorcoil}}}{R_0} \right)^{\alpha_{Cu}} - 1}{\alpha_{Cu}} + T_0, \text{ wherein } T_{\text{motorcoil}} \text{ is the motor coil temperature,}$$

$R_{\text{motorcoil}}$ the resistance of the coil, T_0 the room temperature, α_{Cu} the heat coefficient of the coils' copper and R_0 the resistance of the coil at room temperature.

3. Method according to claim 1 or 2, **characterized in that** the motor coil resistance ($R_{\text{motorcoil}}$) increases with a gradient of about 39%/100°C.
4. Method according to one of the preceding claims, **characterized in that** the special measurement pulse is so short, that the rotor of the motor (7) does not move.
5. Method according to one of the preceding claims, **characterized in that** the special measurement pulse is less than 25 ms.
6. Method according to one of the preceding claims, **characterized in that** the motor coils resistance curve (14) and the ECU resistance curve (15) are stored by polynomial equations.
7. Method according to one of the preceding claims, **characterized in that** the motor coils resistance curve (14) and the ECU resistance curve (15) are stored each by two polynomial equations, one for a first and one for a second part, wherein the first and second part are separated by the minimum of resistance of the ECU resistance curve (15).

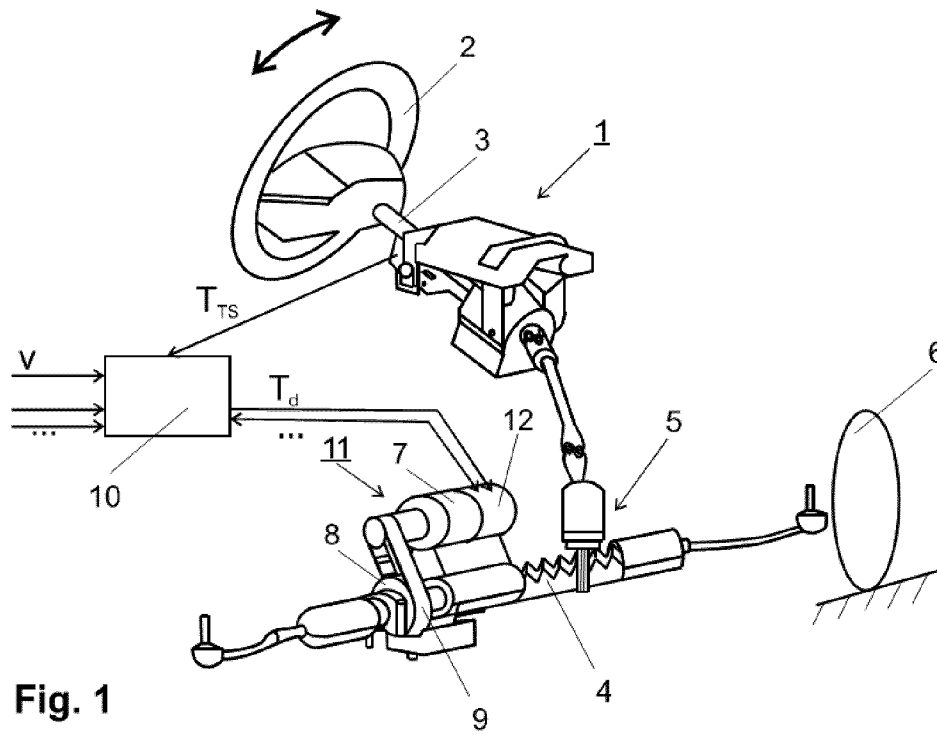


Fig. 1

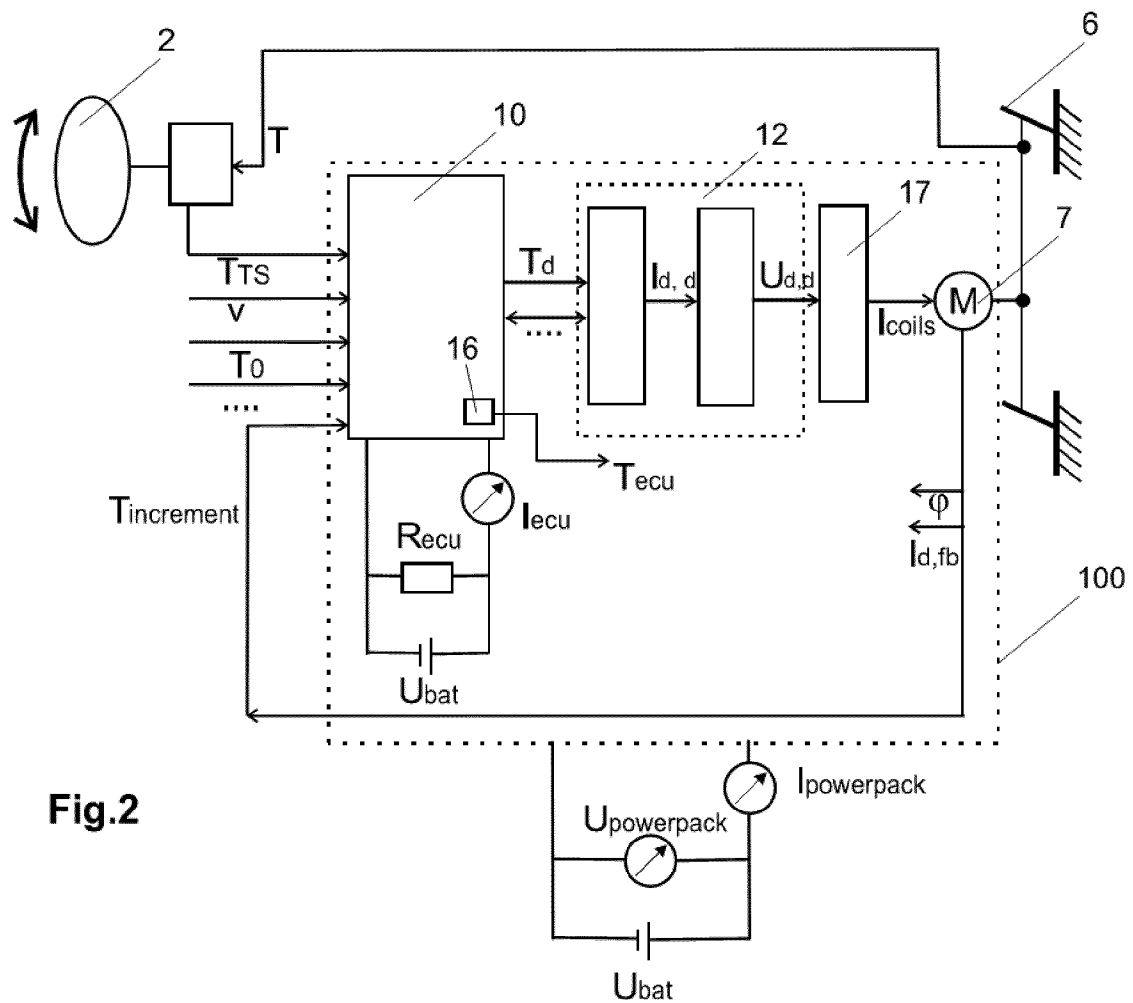
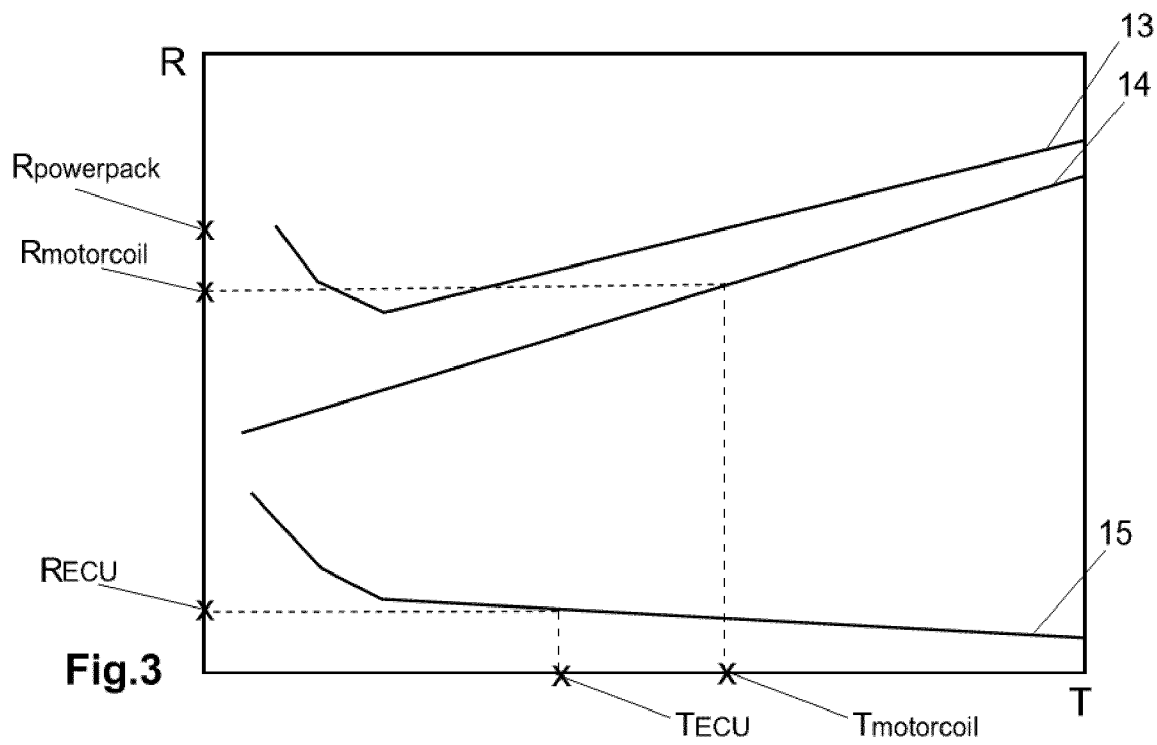


Fig.2



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/062709

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01K7/42 B62D5/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01K B62D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2001 328551 A (TOYOTA MOTOR CORP) 27 November 2001 (2001-11-27) abstract paragraphs [0005] - [0011] -----	1-7
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A	US 2013/033210 A1 (SUZUKI TAKASHI [JP] ET AL) 7 February 2013 (2013-02-07) abstract paragraphs [0037] - [0039] -----	1-7
A	JP 2008 062916 A (NSK LTD) 21 March 2008 (2008-03-21) abstract paragraphs [0003] - [0007] -----	1-7



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/062709

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