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# Australia

*Patents Act 1990*

## Notice Of Entitlement

I, Fraser Patison Old, of 31 Market Street, Sydney, New South Wales, 2000, Australia, being the Patent Attorney for the Applicant/Nominated Person in respect of Application No. 42640/93, state the following:-

The Applicant/Nominated Person has entitlement from the actual inventor as follows:

> The Applicant/Nominated Person, by virtue of a Contract of Employment between the actual inventor as employee and the Applicant/Nominated Person as employer, is a person which would be entitled to have the patent assigned to it if a patent were granted on an application made by the actual inventor.

The Applicant/Nominated Person is the applicant of the application listed in the Declaration under Article 8 of the PCT.

The basic application listed on the Declaration under Article 8 of the PCT is the first application made in a Convention country in respect of the invention.

DATED this Eleventh Day of October 1995

Fraser Patison Old

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**METHOD FOR DETERMINING THE SHORT-CIRCUIT INDUCTANCE OF AN ASYNCHRONOUS MACHINE**

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(71) Applicant(s)
**ABB INDUSTRY OY**

(72) Inventor(s)
**SAMULI HEIKKILA**

(74) Attorney or Agent
**SPRUSON & FERGUSON , GPO Box 3898, SYDNEY NSW 2001**

(56) Prior Art Documents
**GB 2040054**
**EP 441649**
**US 4649341**

(57) Claim

1. A method of determining a short-circuit inductance in an asynchronous machine, where the short-circuit inductance is determined by means of a stator voltage and a stator current derivative of the machine, wherein the method comprises the steps of:

causing a step change in the stator voltage;

measuring both the stator voltage and the stator current derivative both before and after said step change in the stator voltage;

determining the difference between the measured stator voltages and the difference between the measured stator current derivatives; and

determining the quotient of the difference between the stator voltages and the difference between the stator current derivatives for obtaining a short-circuit inductance.

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**(71) Applicant** *(for all designated States except US)*: ABB INDUSTRY OY [FI/FI]; Strömbergintie 1, SF-00380 Helsinki (FI).

**(72) Inventor; and**
**(75) Inventor/Applicant** *(for US only)* : HEIKKILÄ, Samuli [FI/FI]; Pasuunakuja 2 C 28, SF-00420 Helsinki (FI).

**(74) Agent:** OY KOLSTER AB; Stora Robertsgatan 23, P.O. Box 148, SF-00121 Helsinki (FI).



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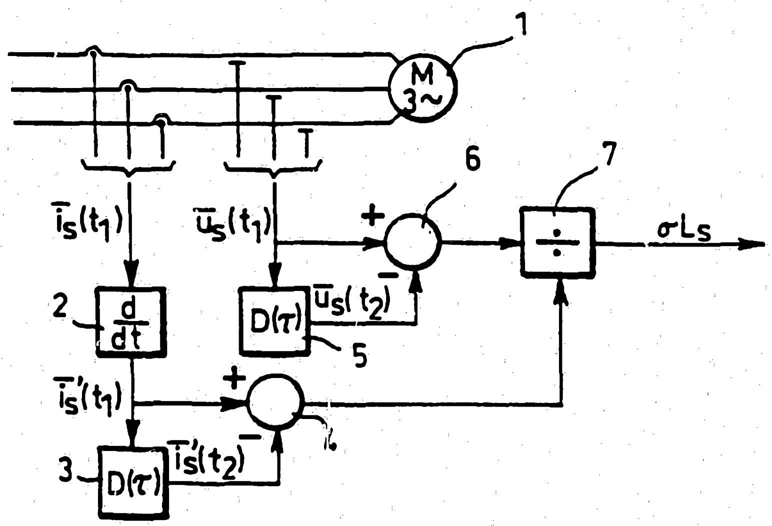
**(54) Title:** METHOD FOR DETERMINING THE SHORT-CIRCUIT INDUCTANCE OF AN ASYNCHRONOUS MACHINE





**(57) Abstract**

The invention relates to a method of determining a short-circuit inductance in an asynchronous machine. To enable the determination of the short-circuit inductance even during the operation of the machine, the method comprises the steps of causing a step change in the stator voltage ($\bar{u}_s$); measuring both the stator voltage ($\bar{u}_s$) and the stator current derivative ($\bar{i}'_s$) both before and after said step change in the stator voltage; determining the difference between the measured stator voltages ($\bar{u}_s(t_1)$, ($\bar{u}_s(t_2)$)) and the difference between the measured stator current derivatives ($\bar{i}'_s(t_1)$), ($\bar{i}'_s(t_2)$)); and determining the quotient of the difference between the stator voltages and the difference between the stator current derivatives for obtaining a short-circuit inductance ($\sigma L_s$).

# Method for determining the short-circuit inductance of an asynchronous machine

This invention relates to a method of determining a short-circuit inductance in an asynchronous machine, wherein the short-circuit inductance is determined by means of a stator voltage and a stator current derivative of the machine.

Control of an asynchronous machine usually aims at a desired behaviour of the torque created by the machine when the current and voltage supplied to the machine are known. One thus attempts to affect the electric torque, the relative value of which as a function of the stator flux and stator current is:

$$T = (\overline{\psi}_s x \overline{i}_s), \qquad (1)$$

where $T$ = electric torque,
$\overline{\psi}$ = stator flux, and
= stator current.

Proper torque control thus requires that not only the current $\overline{i}_s$ but also the stator flux of the machine or a parameter proportional to it (such as the rotor or air gap flux) is known.

Methods for calculating the stator flux are based on the well-known differential and current equations of the stator and rotor of an asynchronous machine, which are as follows in the coordinate system of the stator:

$$\overline{u}_s = R_s\overline{i}_s + \frac{d\overline{\psi}_s}{dt} \qquad (2)$$

$$0 = R_r\bar{i}_r + \frac{d\bar{\Psi}_r}{dt} - j\omega_m\bar{\Psi}_r \qquad (3)$$

$$\bar{\Psi}_s = L_s\bar{i}_s + L_m\bar{i}_r \qquad (4)$$

$$\bar{\Psi}_r = L_r\bar{i}_r + L_m\bar{i}_s \qquad (5)$$

where $\bar{\Psi}_r$ = rotor flux,
$\bar{i}_r$ = rotor current,
$\bar{u}_s$ = stator voltage,
$R_s$ = stator resistance,
$R_r$ = rotor resistance,
$L_s$ = stator inductance,
$L_r$ = rotor inductance,
$L_m$ = primary inductance, and
$\omega_m$ = mechanical rotation rate.

The object is to calculate the stator flux by means of the measured stator current and stator voltage, and so the rotor flux and rotor current have to be eliminated from the above equations. Using Eq. 4 and 5, the rotor flux and rotor current are first solved as a function of the stator flux and stator current:

$$\bar{\Psi}_r = \frac{L_r}{L_m}(\bar{\Psi}_s - \sigma L_s\bar{i}_s) \qquad (6)$$

$$\bar{i}_r = \frac{1}{L_m}(\bar{\Psi}_s - L_s\bar{i}_s), \qquad (7)$$

where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ = dispersion coefficient, and

$\sigma L_s$ = short-circuit inductance.

Using Eq. 6 and 7, Eq. 2 and 3 are reduced into the following form:

$$\frac{d\overline{\psi}_s}{dt} = \overline{u}_s - R_s \overline{i}_s \tag{8}$$

$$\frac{d\overline{\psi}_s}{dt} = \sigma L_s \frac{d\overline{i}_s}{dt} - \frac{1}{\tau_r}(\overline{\psi}_s - L_s \overline{i}_s) + j\omega_m(\overline{\psi}_s - \sigma L_s \overline{i}_s), \tag{9}$$

where $\tau_r = \frac{L_r}{R_r}$ = rotor time constant.

Most prior art stator flux calculation methods utilize either Eq. 8 or Eq. 9 or both of them. When using Eq. 8 alone, it is not possible to effect proper control at very low frequencies, wherefore the best methods always use either Eq. 9 or both equations.

One crucial parameter required in Eq. 9 is the short-circuit inductance. To deduce one method for calculating it, the derivative of the rotor flux is discussed first, which is on the basis of Eq. 2 and 6:

$$\frac{d\overline{\Psi}_r}{dt} = \frac{L_r}{L_m}\left(\frac{d\overline{\Psi}_s}{dt} - \sigma L_s \frac{d\overline{i}_s}{dt}\right)$$

$$= \frac{L_r}{L_m}\left(\overline{u}_s - R_s\overline{i}_s - \sigma L_s \frac{d\overline{i}_s}{dt}\right) \qquad (10)$$

Introducing Eq. 10 into Eq. 3 gives:

$$\sigma L_s \frac{d\overline{i}_s}{dt} = \overline{u}_s + \overline{u}_0, \qquad (11)$$

where $\overline{u}_0$ is a voltage depending on the state of the machine:

$$\overline{u}_0 = \frac{L_m}{L_r}(R_r\overline{i}_r - j\omega_m\overline{\Psi}_r) - R_s\overline{i}_s \qquad (12)$$

At the starting time of the asynchronous machine (indicated with the reference $t_0$) the stator and rotor currents and fluxes are zero, so that $\overline{u}_0(t_0) = 0$, and it follows from Eq. 11 that

$$\sigma L_s\overline{i}_s'(t_0) = \overline{u}_s(t_0), \qquad (13)$$

where $\overline{i}_s'(t_0)$ is the derivative of the stator current at the time $t_0$.

Accordingly, the stator current starts to increase in the direction of the stator voltage with a slope $\overline{u}_s(t_0)/\sigma L_s$ when a predetermined voltage $\overline{u}_s(t_0)$ is supplied to an unmagnetized machine. The situation is illustrated in Figure 1, which shows a voltage $u_s$ and a current $i_s$ as a function of time in a starting situation described above.

One prior art way of determining $\sigma L_s$ is, in fact, based on measuring the stator voltage and the derivative of the stator current of the machine at the starting time, and so the short-circuit inductance can be calculated on the basis of Eq. 13 directly as a ratio between them:

$$\sigma L_s = \frac{\bar{u}_s(t_0)}{\bar{i}_s'(t_0)} \qquad (14)$$

A drawback of the above-described method is that $\sigma L_s$ is determined only at the starting time, whereafter it is assumed to remain constant. Like the other inductances of a machine, the short-circuit inductance may actually vary considerably during operation due to the fact that the saturation state of the magnetic flux of the stator or the rotor varies with the operating point of the machine.

The object of the present invention is to provide a method ( determining a short-circuit inductance estimate, which does not have the limitations and problems described above and which may be applied during the operation of the machine as well. This is achieved by means of a method according to the invention, which is characterized in that it comprising the steps of causing a step change in the stator voltage; measuring both the stator voltage and the stator current derivative both before and after said step change in the stator voltage; determining the difference between the measured stator voltages and the difference between the measured stator current derivatives; and determining the quotient of the difference between the stator voltages and the difference between the stator current derivatives for obtaining a short-circuit inductance.

In the method, an unknown voltage component $\bar{u}_0$

deviating from zero during the normal operation of the machine is eliminated from Eq. 11 so that in place of observing an individual value of the derivative of the stator current one observes a change caused in it by a step change in the stator voltage.

In the following the invention will be described in greater detail with reference to the attached drawings, in which

Figures 1a and 1b show examples of the absolute values of the stator voltage and the stator current, respectively, as a function of time, when the stator voltage of an unmagnetized machine undergoes a step change at a time $t_0$;

Figures 2a and 2b show examples of the absolute values of the stator voltage and the stator current, respectively, as a function of time, when the stator voltage of a magnetized rotating machine undergoes a step change at a time $t_c$;

Figure 3 is a flow chart illustrating a method of estimating the short-circuit inductance of an asynchronous machine according to the invention; and

Figure 4 is a flow chart illustrating how the method of estimating the short-circuit inductance in an asynchronous machine according to the invention is applied in a torque control method for an asynchronous machine.

Assume that the stator voltage of a magnetized rotating asynchronous machine undergoes a step change at a time $t_c$, and that the stator voltage and the derivative of the stator current have been measured a little before this change at a time $t_2$ and a little after the change at a time $t_1$ (Figure 2). As Eq. 11 is valid both at the time $t_1$ and the time $t_2$, the following interdependence will occur between the measured parameters:

$$\sigma L_s \bar{i}_s'(t_1) = \bar{u}_s(t_1) + \bar{u}_0(t_1) \qquad (15)$$

$$\sigma L_s \bar{i}_s'(t_2) = \bar{u}_s(t_2) + \bar{u}_0(t_2) \qquad (16)$$

In practice, the currents and fluxes of an asynchronous machine are not capable of changing step by step, so that, according to Eq. 12, the voltage component $\bar{u}_0$ is a continuous function in the time domain, for which is true:

$$\lim_{t \to t_c^-}\{\bar{u}_0(t)\} = \lim_{t \to t_c^+}\{\bar{u}_0(t)\} = \bar{u}_0(t_c) \qquad (17)$$

When the measuring times $t_1$ and $t_2$ are set very close to the time of change $t_c$, it follows from Eq. 17:

$$\bar{u}_0(t_1) \approx \bar{u}_0(t_2) \qquad (18)$$

The values of the derivative of the stator current should thus be measured immediately before and immediately after the time of change of the stator voltage. In practice, this means that the derivatives of the stator current are determined e.g. about 100 µs before and after the change of the stator voltage in a machine having a rotor time constant of about 100 ms. Generally speaking, it is conceivable that the time lapse between each measuring time and the time of change of the stator voltage is set such that it is no more than one thousandth part of the rotor time constant of the machine.

When both sides of Eq. 16 are subtracted from the respective sides of Eq. 15, and the approximate equation 18 is applied, one gets:

$$\sigma L_s(\bar{i}_s'(t_1)-\bar{i}_s'(t_2)) = \bar{u}_s(t_1)-\bar{u}_s(t_2)+\bar{u}_0(t_1)-\bar{u}_0(t_2)$$

$$\approx \bar{u}_s(t_1)-\bar{u}_s(t_2) \qquad (19)$$

It is noted that when the stator voltage undergoes a step change, a corresponding change in the derivative of the stator current depends only on the magnitude of the voltage change besides the short-circuit inductance. An individual current derivative depends both on the stator voltage and the voltage $\bar{u}_0$ (Eq. 11), which, however, is reduced in Eq. 19, as $\bar{u}_0(t)$ is constant over a short period of time irrespective of the variation in the supply voltage.

By solving Eq. 19 with respect to $\sigma L_s$, it is noted that the short-circuit inductance estimate can be calculated by dividing the instantaneous change of the stator voltage by the corresponding change of the derivative of the stator current:

$$\sigma L_s = \frac{\bar{u}_s(t_1)-\bar{u}_s(t_2)}{\bar{i}_s'(t_1)-\bar{i}_s'(t_2)} \qquad (20)$$

The method according to the invention is illustrated by means of the flow chart in Figure 3, in which the symbol $\tau$ is used to represent the time difference between the measuring times $t_1$ and $t_2$:

$$t_1 - t_2 = \tau \qquad (21)$$

In blocks 3 and 5, a delay operator D is used, which is defined as follows:

$$D(\tau)f(t) = f(t-\tau), \tag{22}$$

where f is an arbitrary function of t delayed by a period of time corresponding to $\tau$ when multiplied by $D(\tau)$.

It is further required in the method of Figure 3 that there occurs a step change in the stator voltage between the times $t_1$ and $t_2$. This requirement does not involve practical problems as typical asynchronous machine applications requiring parameter identification are usually based on frequency converters controlling the stator voltage step by step. The estimation of $\sigma L_s$ should only be synchronized so that changes in the stator voltage fall between the times $t_1$ and $t_2$.

In Figure 3, the stator current $\bar{i}_s(t_1)$ of the asynchronous machine 1, obtained by measuring at the time $t_1$, is first differentiated in block 2 to obtain a derivative $\bar{i}_s'(t_1)$. In block 3, $\bar{i}_s'(t_1)$ is delayed by a period of time corresponding to $\tau$, so that $\bar{i}_s'(t_2)$ is obtained from the output of this block. Block 4 is a summing means, in which the latter delayed derivative is subtracted from the previous one, and the output of which corresponds to the denominator of Eq. 20. Correspondingly, the stator voltage $\bar{u}_s(t_1)$ obtained by measuring at the time $t_1$ is first delayed by a period of time corresponding to $\tau$ in block 5 to obtain $\bar{u}_s(t_2)$. Thereafter the latter delayed voltage is subtracted from the previous one in block 6, the output of which corresponds to the numerator of Eq. 20. Finally, the output of block 6 is divided in block 7 by the output of block 4 to obtain the short-circuit inductance estimate based on Eq. 20.

Figure 4 is a flow chart illustrating the application of the method according to the invention in a method of controlling torque in an asynchronous machine. The measured stator current and stator voltage of the asynchronous machine 1 are input parameters applied to block 8, which corresponds to the short-circuit inductance estimation method illustrated in Figure 3. The output parameter $\sigma L_s$ from block 8, $\bar{i}_s$ and $\bar{u}_s$ and the parameters $R_s$, $L_s$, $\tau_r$ and $\omega_m$ assumed to be known are applied to the input of block 9, from the output of which a stator flux estimate satisfying Eq. 9 as accurately as possible is obtained. The flux estimate from block 9 and the measured stator current are applied to the input of block 10, in which a torque estimate T is calculated by using the cross product (Eq. 1). In block 11, a reference value $T_{ref}$ of the torque is subtracted from the obtained torque estimate so as to obtain a control parameter $\mu$. Block 12 is a controller which aims at creating, on the basis of said control parameter, an effect increasing the torque if $\mu<0$, and correspondingly an effect decreasing the torque if $\mu>0$, by varying the current or voltage supplied to the machine.

The claims defining the invention are as follows:

1. A method of determining a short-circuit inductance in an asynchronous machine, where the short-circuit inductance is determined by means of a stator voltage and a stator current derivative of the machine, wherein the method comprises the steps of:

causing a step change in the stator voltage;

measuring both the stator voltage and the stator current derivative both before and after said step change in the stator voltage;

determining the difference between the measured stator voltages and the difference between the measured stator current derivatives; and

determining the quotient of the difference between the stator voltages and the difference between the stator current derivatives for obtaining a short-circuit inductance.

2. The method of determining a short-circuit inductance in an asynchronous machine substantially as hereinbefore described with reference to Figs. 2 to 4 of the accompanying drawings.

DATED this Eleventh Day of October 1995

**ABB Industry OY**

Patent Attorneys for the Applicant

SPRUSON & FERGUSON

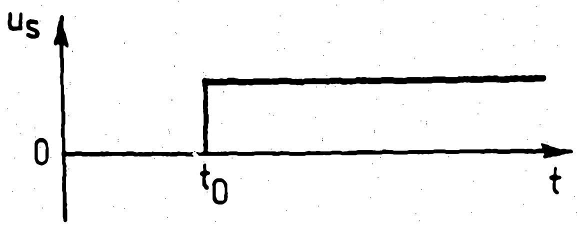



FIG. 1a

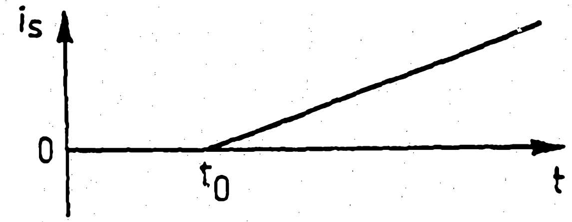



FIG. 1b

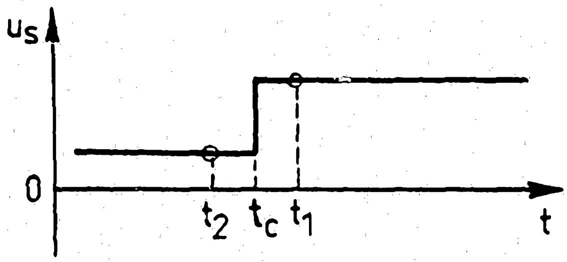



FIG. 2a

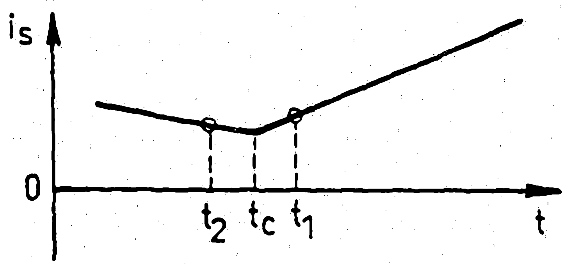



FIG. 2b

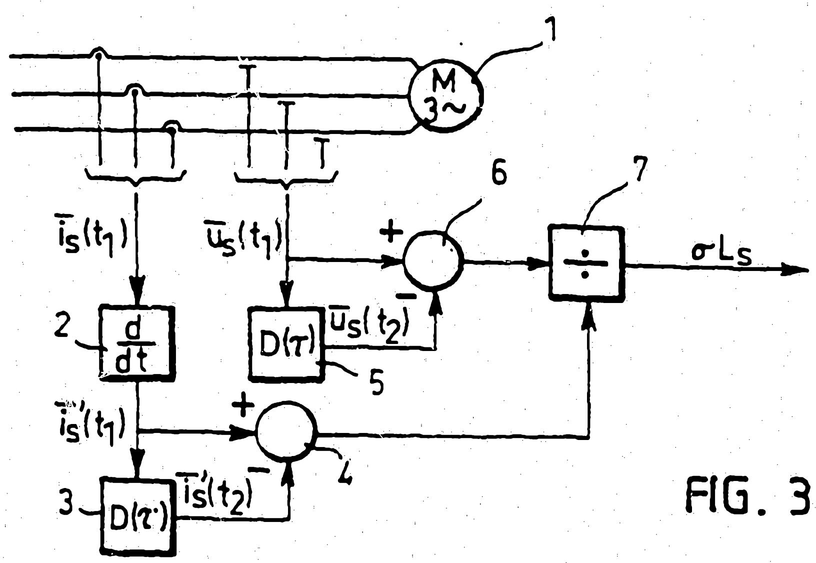



FIG. 3

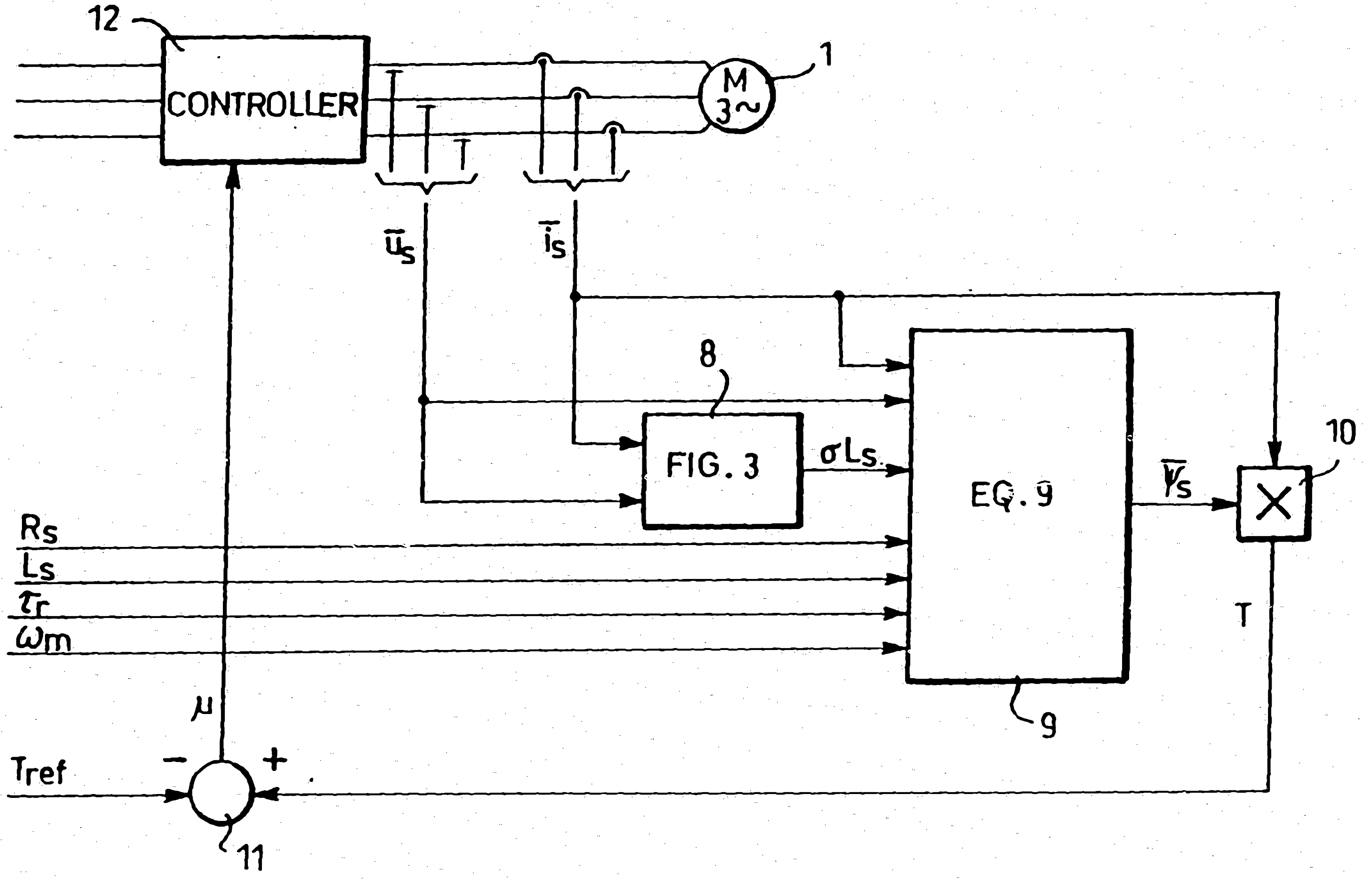

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FIG. 3
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FIG. 4

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI 92/00354

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC5: G01R 27/26
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)

IPC5: G01R

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

SE,DK,FI,NO classes as above

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

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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| A | GB, A, 2059604 (ROBERT BOSCH GMBH), 23 April 1981 (23.04.81), abstract<br>-- | 1 |
| A | EP, A1, 0288704 (WABCO WESTINGHOUSE FAHRZEUGBREMSEN GMBH), 2 November 1988 (02.11.88)<br>-- | 1 |

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 5 March 1993 | 31 -03- 1993 |
| Name and mailing address of the ISA/<br>Swedish Patent Office<br>Box 5055, S-102 42 STOCKHOLM<br>Facsimile No. +46 8 666 02 86 | Authorized officer<br><br>Sven-Olof Wirlée<br>Telephone No. +46 8 782 25 00 |

INTERNATIONAL SEARCH REPORT

| International application No. |
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| PCT/FI 92/00354 |

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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**INTERNATIONAL SEARCH REPORT**
Information on patent family members

29/01/93

International application No.
PCT/FI 92/00354

| Patent document cited in search report | | Publication date | Patent family member(s) | | Publication date |
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| EP-A2- | 0441649 | 14/08/91 | NONE | | |
| US-A- | 4649341 | 10/03/87 | DE-A- | 3343885 | 25/10/84 |
| | | | EP-A,B- | 0126846 | 05/12/84 |
| | | | SE-T3- | 0126846 | |
| | | | EP-A- | 0358241 | 14/03/90 |