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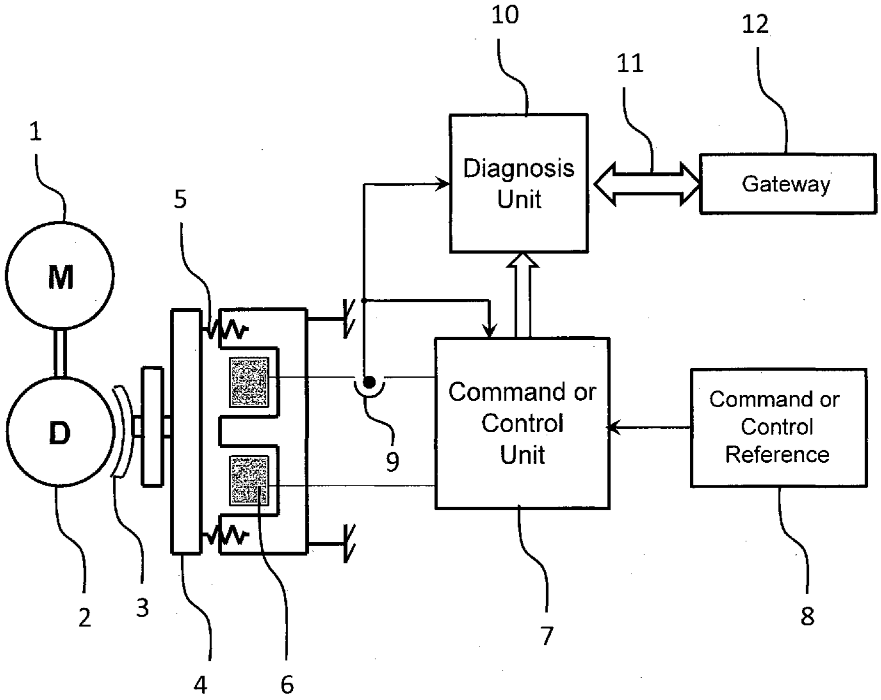
# (54) Title: DIAGNOSIS DEVICE FOR ELECTROMAGNETIC BRAKE

FIG.1



**(57) Abstract:** The present invention discloses a diagnosis device for electromagnetic brakes used in motion control systems, safety related applications or safety critical systems. The diagnosis of electromagnetic brake is performed sensing only the applied voltage and measured current, so it is a cost- effective solution. Based on the sensed electrical variables the armature speed and position are estimated using a piecewise linear state-observer. Next, fault-detection and fault-isolation is performed using the estimated speed and position. The outcome of the fault-isolation is shown on a status indicator and is also transmitted to a gateway using a communication link, so remote diagnosis is possible.

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*[Continued on next page]*

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# [DESCRIPTION]

## [Title of Invention]

DIAGNOSIS DEVICE FOR ELECTROMAGNETIC BRAKE

## [Technical Field]

[0001]

The present invention is generally directed to diagnosis of an electromagnetic brake used in motion control systems such as elevators, escalators, motor drives, etc, and more particularly, the present invention is directed to an improved, higher reliability fault-detection having a state-observer based position and speed estimation section, a fault-detection and fault-isolation section as well as a status indicator. Furthermore, the fault-isolation section is connected via a communication link to a gateway, so the electromagnetic brake can be remotely diagnosed.

## [Background Art]

[0002]

Electromagnetic actuators are widely used in different industrial sectors. Patent Literature 1 discloses an industrial robot having a plurality of independently controlled electromagnetic brakes. Patent Literature 2 is disclosing an electromagnetic actuator driving method, in particular for actuating valves in an internal combustion engine. Patent Literature 3 as well Patent Literature 4 are disclosing a methods and devices for operating and diagnosing injection valves.

[0003]

Furthermore, in many industrial applications, monitoring the armature position of an electromagnetic brake is essential, this is especially true for safety related or safety critical applications, where the electromagnetic actuator is part of a safety-loop or safety-chain as an end actuator, bringing the system to a safe state.

[0004]

The armature position of an electromagnetic brake is usually monitored by a sensor/sensing device, such as capacitive displacement sensor, infra-red displacement sensor, acceleration sensor, switches or a micro-switch, etc., but so-called “sensorless” solutions in which mechanical variables, e.g. speed or position are not measured are also known.

[0005]

Using a switch or a micro-switch to monitor the armature position is a cost effective solution. However, a switch contains moving mechanical part, thus the reliability of the monitoring solution depends at least on the initial setting of the switch/micro-switch and its wear in time.

[0006]

Using a sensor/sensing device to monitor the armature movement and/or position are less cost effective due to the imposed strict technical requirements. These strict technical requirements are due to: limited range of the armature movement, operating temperature range of the electromagnetic brake and/or strong electromagnetic field generated by the electromagnetic actuator itself. However, sensor based monitoring solutions can achieve good reliability.

[0007]

For example Patent Literature 5 is disclosing a sensor based self-diagnosis method of braking performance of an elevator, where the self-diagnosis is performed by measuring and comparing the braking distance, after the brake is applied when the elevator runs at rated speed. Although, the disclosed method can diagnose the braking performance it requires a test run of the elevator.

[0008]

In a similar manner, Patent Literature 6 is disclosing a failure diagnosis device for elevator electromagnetic brake, having an acceleration sensor by detecting the acceleration of the brake plunger when is operated. The disclosed diagnosis device requires an acceleration sensor, which often is not a cost effective solution.

[0009]

In addition Patent Literature 7 is disclosing an elevator braking device diagnostic apparatus, where the displacement of the plunger, which us stored in a data storage unit, and the average value of the displacement over a defined elevator operation cycle are subtracted and compared with a predefined threshold.

[0010]

Related to “sensorless” solutions, they usually measure electrical variables such as e.g. voltage and current and based on that, mechanical variables, such as speed and position are estimated.

[0011]

Patent Literature 8 and Patent Literature 9 are disclosing a method for estimating the brake pressing force and the brake stroke based on the drop-away starting current when the brake drops and the attraction starting current when the brake is attracted. Although, the disclosed method estimates the brake pressing force and brake stroke using a pull-up and release cycle it cannot estimate the brake stroke only based on armature pull-up or armature release.

[0012]

Furthermore Patent Literature 10 is disclosing a detection method, for armature movement of an electromagnetic brake by comparing the estimated induced electromotive force with a set of threshold levels. However, the simplified mathematical model does not allow accurate estimation in case of large air-gaps.

[0013]

Often – in case of electromagnetic actuators - an additional signal is injected in order to calculate/estimate the electromagnetic inductance denoted by $\mathbf{L_m}$, since there is a known relation between electromagnetic inductance and position denoted by $\mathbf{z}$, such as: $\mathbf{L_m} = \mathbf{L_m(z)}$.

[0014]

Taking the inverse of $\mathbf{L_m} = \mathbf{L_m(z)}$ function the armature position ($\mathbf{z}$) can be calculated/estimated.

[0015]

However, such solutions are often limited in terms of precision since the electromagnetic inductance is not only armature position dependent but also depends on armature current denoted by $\mathbf{i}$, $\mathbf{L_m} = \mathbf{L_m(i, z)}$.

[0016]

Furthermore, there are application fields where the additional signal can be injected only for limited time, or its amplitude must be severely limited or the injection of additional signal is forbidden. Moreover, such solutions might estimate the armature position for two different operating points, but deriving armature speed between the two operating points usually is less accurate.

[0017]

In this sense, Patent Literature 10 is disclosing an armature position estimation method by estimating the electromagnetic inductance when a certain current pattern is injected using a hysteresis controller.

[0018]

The current through the coil of the electromagnetic actuator usually is controlled via an electronic switch using pulse width modulation. In this sense, Patent Literature 11 describes a method for regulating the current flow through an electromagnetic actuator by means of pulse width modulation (PWM).

[0019]

Observer-based solutions are also known – for example angular speed and angular position estimation of electric machines. These solutions are model-based, assuming in most of the cases a linear model for the electric machine - assumption, which is true as long as the electric machine is not magnetically saturated.

[0020]

Patent Literature 12 and Patent Literature 13 are disclosing a device for determine the position of the rotor based on the input current as well as a system and method for determining electrical angles of electric motors at zero and low speeds without using angle sensors.

[0021]

Patent Literature 14 and Patent Literature 15 are disclosing a state and parameter estimator, such as state of charge and open circuit voltage estimator, applied for electrical energy accumulators as well as electrical energy accumulators.

[0022]

Furthermore, observer-based solutions are used to estimate lateral velocity of a vehicle as well as the dynamic load of a vehicle.

[0023]

Patent Literature 16 is discloses a system, which estimates the lateral velocity of a vehicle by minimizing an error between the estimated and measured axle forces.

[0024]

**Patent Literature** 17 is disclosing a system and a method for calculating an estimated load on the tire from the measured static load, the vehicle roll angle, the vehicle lateral and longitudinal acceleration.

**[Citation List]**

**[Patent Literature]**

[0025]

**[PTL 1]**

EP1974970A1

**[PTL 2]**

EP1262639B1

**[PTL 3]**

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**[PTL 4]**

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**[PTL 5]**

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**[PTL 6]**

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**[PTL 7]**

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**[PTL 11]**

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**[PTL 12]**

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**[PTL 13]**

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**[PTL 14]**

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**[PTL 15]**

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**[PTL 16]**

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**[PTL 17]**

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[**Non Patent Literature**]

[0026]

**[NPL 1]**

D.G. Luenberger: Observers for multivariable systems. IEEE Transactions on Automatic Control, vol. 11, no. 2, 1966, pp. 190-197.

**[NPL 2]**

R.C. Leishman, J.C. Macdonald Jr., R.W. Beard T.W. McLain: Quadrotors and accelerometers - state estimation with an improved dynamic model. IEEE Control Systems Magazine, Vol. 34, No. 1, February 2014, pp. 28-41.

**[Summary of Invention]**

**[Technical Problem]**

[0027]

An observer-based solution can be applied for an electromagnetic actuator, too. However, the electromagnetic actuator is a highly nonlinear system, so such solutions cannot be applied directly. The electromagnetic flux and electromagnetic force are current and armature position dependent.

[0028]

As summary, sensor-based solutions offer good diagnosis reliability but are not cost effective. On the other hand, model-based “sensorless” solutions are desired from cost point of view but the reliability of the diagnosis depends on the accuracy of the model and the used estimation method.

[0029]

Therefore, the diagnosis device proposed in this invention is going to overcome those disadvantages.

**[Solution to Problem]**

[0030]

The present inventions relates to “sensorless” diagnosis of electromagnetic brakes. The operation of the electromagnetic brake, can be divided in three regions including normal, under warning and faulty operation, is diagnosed using only the detected current through the electromagnetic brake coil and the applied input voltage. Therefore, only the electrical variables of the electromagnetic brake are sensed and no sensors or sensing devices are used to detect mechanical variables such as armature position or armature speed.

[0031]

Due to the fact that the sensors detecting mechanical variables are eliminated the proposed solution is cost effective. Furthermore, diagnosing the operation of the electromagnetic brake can be a requirement in safety related applications, where the brake is the end actuator of the safety loop.

[0032]

The proposed "sensorless" diagnosis method is model-based, using a piecewise linear mathematical model of the electromagnetic brake which is a nonlinear system and piecewise linear observer.

[0033]

The diagnosis device – disclosed in the present invention - comprises a current and voltage monitoring sections, which monitor the electromagnetic actuator current and applied voltage, a piecewise linear state-observer section, which estimates the armature position and speed, a fault-detection section, which detects the armature movement and based on the estimated position and speed values calculates the fault isolation measure which is a diagnosis value by using an Euclidean norm, a fault-isolation section, which clusters the diagnosis value into one of the following regions: normal/warning/faulty.

[0034]

Since in most cases the spring force is undergoing variation due to settings and manufacturing dispersion, a so-called "unknown input observer" is used to estimate the spring force.

[0035]

The fault-isolation section of the diagnosis device displays the status including e.g. normal, warning and faulty of the electromagnetic brake as well as sends this information via a communication link to a gateway so remote diagnosis is possible.

**[Brief Description of the Drawings]**

[0036]

**[Fig. 1]**

FIG. 1 is a schematic view showing a possible application of the diagnosis device according to embodiments of the present invention.

**[Fig. 2]**

FIG. 2 is a schematic view of the diagnosis unit - as well as the first embodiment of the present invention - showing the main elements of the diagnosis device.

**[Fig. 3]**

FIG. 3 is an illustrative example showing armature current and position for normal operation as well as for armature locked operation according to the first embodiment of the present invention.

**[Fig. 4]**

FIG. 4 shows operating regions including e.g. normal, warning and faulty for the electromagnetic brake during pull-up and release according to the first embodiment of the present invention, wherein the operating regions are defined in the coordinate system $\mathbf{\Delta z} - \mathbf{\Delta Ec}$, where $\mathbf{\Delta z}$ is the variation of armature displacement and $\mathbf{\Delta Ec}$ is the variation of kinetic energy of the moving armature.

**[Fig. 5]**

FIG. 5 is a detailed view of the piecewise linear observer according to embodiments of the present invention, which resembles the well-known Luenberger state-observer.

**[Fig. 6]**

FIG. 6 is a schematic view of the diagnosis unit - as well as the second embodiment of the present invention - showing the main elements of the diagnosis device.

**[Fig. 7]**

FIG. 7 is a detailed view of unknown input observer used for spring force estimation according to the second embodiment of the present invention.

**[Fig. 8]**

FIG. 8 is an illustrative example of the armature speed (solid line) and estimated speed (dashed line) during armature pull-up and release according to the second embodiment of the present invention.

**[Fig. 9]**

FIG. 9 is an illustrative example showing the operating regions for a practical case during armature pull-up and release according to the second embodiment of the present invention.

## [Description of Embodiments]

### [Example 1]

[0037]

Hereinafter, reference will be made to one example of diagnosis device for electromagnetic brakes.

[0038]

In FIG. 1, the electrical machine 1 which is e.g. an execution element in a motion control system is connected to a brake drum/disk 2, on which the brake shoe 3 is applied, when the electromagnetic brake - comprising a moving armature 4, mechanical springs 5 and coil 6 - is released. The electromagnetic brake is commanded including pulled-up and release commands or controlled via the control unit 7, which receives the command or control reference from section 8. The electric current through the brake coil is sensed via a sensor or sensing device 9 and the information is sent to the control unit 7 as well as diagnosis unit 10, which also receives as input the applied voltage on the electromagnetic brake, defined by section 7. The diagnosis unit 10 is connected via a communication link 11 to the gateway

12, so remote diagnosis of the electromagnetic brake is possible.

The electromagnetic brake has an electromagnetic actuator or an armature which includes the moving armature 4, the mechanical springs 5, the coil 6. The sensing device 9 forms a current detector. **The diagnosis device may also have a voltage detector (not shown) for detecting applied input voltage on the electromagnetic brake, if it necessary.**

[0039]

The command/control unit can be a simple switch or a half H-bridge and the current sensor or sensing device can be a simple resistor or a current sensor e.g. based on Hall-effect.

[0040]

The state-space representation of the electromagnetic brake is written in the following form with the usual notations:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u}$$

where:

$\boldsymbol{x}$ is the state-space vector $\boldsymbol{x} = [i \quad z \quad v]^T$ and ($i$) is the armature current, ($z$) is the armature position and ($v$) is the armature speed

$\boldsymbol{u} = [\boldsymbol{V}_{in} \quad \boldsymbol{F}_s]^T$ is the input vector where (**Vin**) is the applied voltage and (**Fs**) is the spring force

$\boldsymbol{y}$ is the output vector

***A, B, C*** and ***D*** are state-space matrices - reference to them will be made later

and $\boldsymbol{T}$ is the transpose operator.

[0041]

The state-space matrices **A**, **B** are not constant, since the electromagnetic brake which is an actuator is a nonlinear system. In this case the state-space matrices $\boldsymbol{A} = \boldsymbol{A}(\boldsymbol{i}, \boldsymbol{z}), \boldsymbol{B} = \boldsymbol{B}(\boldsymbol{i}, \boldsymbol{z})$ are parameter dependent matrices, depending on the armature current and armature position.

[0042]

The $\boldsymbol{C}$ and $\boldsymbol{D}$ matrices are constant: $\boldsymbol{C} = [\mathbf{1} \quad \mathbf{0} \quad \mathbf{0}]$ if only the armature current is measured and $\mathbf{D} = \mathbf{0}$.

[0043]

The preferred first embodiment of the present invention is shown in FIG. 2.

[0044]

According to the first embodiment of the present invention (FIG. 2) the state observer 13 which is e.g. a piecewise linear observer receives its inputs, armature current (**i**), applied voltage (**Vin**) and spring force (**Fs**) based on which it estimates the state vector ($\hat{\boldsymbol{x}}$). Hereby, it is assumed that the spring force (**Fs**) is constant and is known in advance. Reference to the state observer 13 will be made later in this embodiment of the invention.

[0045]

Next, let us denote with ($\mathbf{t_1}$) and ($\mathbf{t_2}$) the time moments when the armature starts to move and the armature movement stops respectively.

[0046]

The above mentioned time moments can be calculated by comparing the estimated position ($\hat{\boldsymbol{z}}$) or estimated speed ($\hat{\boldsymbol{v}}$) with certain threshold values.

[0047]

However, a more reliable solution to detect the armature movement is by comparing the absolute value of the first derivate of the current estimation error with a certain positive threshold.

[0048]

Here the current estimation error denoted by $e_l$ is the error between the measured current (**i**) and the estimated current ($\widehat{\imath_l}$).

$$e_l = i - \widehat{\imath_l}$$

[0049]

Here, the subscript (*l*) in the above equation denotes that the estimate is calculated based on the model with locked armature.

[0050]

Typical armature current waveforms and armature position are shown in FIG. 3 for normal operation as well as for armature locked operation.

[0051]

For the model with locked armature, the armature initial position is denoted by ($\mathbf{z_0}$), where: ($\mathbf{z_0} = \mathbf{z_{min}}$) in case of armature release and ($\mathbf{z_0} = \mathbf{z_{max}}$) in case of armature pull-up. The armature release or pull-up operation is uniquely defined by the applied voltage (**Vin**) via section 8 and section 7 as shown in FIG. 1

[0052]

The corresponding state-space matrices when the armature is locked into ($\mathbf{z_0}$) initial position are denoted as $\boldsymbol{A_l} = \boldsymbol{A_l}(\widehat{\imath_l}, \boldsymbol{z_0})$, $\boldsymbol{B_l} = \boldsymbol{B_l}(\widehat{\imath_l}, \boldsymbol{z_0})$. The other matrices are $\mathbf{C}_l = \mathbf{1}$ and $\mathbf{D}_l = \mathbf{0}$. For the given state-space representation the first-order differential equation can be solved and the estimated current ($\widehat{\imath_l}$) can be calculated for the model with locked armature.

[0053]

The armature starts to move when the absolute value of error derivate ($|\mathbf{de_l/dt}|$) exceeds a certain positive threshold ($|\mathbf{de_l/dt}| > \mathbf{TH1}$). This time moment corresponds to the time moment denoted by ($\mathbf{t_1}$). Hereby, (**TH1**) is a strictly positive constant.

[0054]

After the armature started its movement, the first derivate of the error is compared ($|\mathbf{de_I/dt}| < \mathbf{TH2}$), where (**TH2**) is a second threshold, in order to detect that the armature movement is stopped, which corresponds to the time moment denoted by ($\mathbf{t_2}$). In this case (**TH2**) a positive constant.

[0055]

Next, based on the estimated position ($\hat{\boldsymbol{z}}$) and estimated speed ($\hat{\boldsymbol{v}}$) the fault-detection section 14 calculates the estimated armature displacement denoted by ($\widehat{\boldsymbol{\Delta z}}$) and the estimated kinetic energy variation of the moving armature denoted by ($\widehat{\boldsymbol{\Delta Ec}}$).

$$\widehat{\Delta z} = \int_{t1}^{t2} \hat{v}\, dt$$

[0056]

The variation of the kinetic energy of the moving mass is calculated as:

$$\widehat{\Delta \mathrm{Ec}} = m \int_{\widehat{v1}}^{\widehat{v2}} \hat{v}\, dv$$

where (**m**) is the moving mass which is known in advance with good accuracy, ($\hat{\boldsymbol{v}}_{\mathbf{1}}$) and ($\hat{\boldsymbol{v}}_{\mathbf{2}}$) are the estimated speeds corresponding to time moments ($\mathbf{t_1}$) and ($\mathbf{t_2}$).

[0057]

Based on these two values ($\widehat{\boldsymbol{\Delta z}}$) and ($\widehat{\boldsymbol{\Delta Ec}}$) the Euclidean distance of armature stroke and kinetic energy is calculated, which is a fault-detection indicator/measure denoted by **Fd**.

$$\boldsymbol{F_d^2} = (\widehat{\boldsymbol{\Delta z}})^2 + (\widehat{\boldsymbol{\Delta Ec}})^2$$

[0058]

The fault-detection indicator/measure (**Fd**) is using both the estimated stroke and estimated speed – it combines them in a single metric for better fault-detection as explained below.

[0059]

Using only the armature stroke as a fault-detection indicator/measure might be sufficient in several applications. However, including the estimated kinetic energy can enhance the fault-detection process. For example: during operation the armature stroke is nominal/normal, however the estimated kinetic energy which is based on the estimated speed is lower than the nominal/normal values. This is an indication of slow/slower armature pull-up/release, which can raise a warning indication and can be essential especially in safety related application, where brake pull-up/release time can be a requirement.

[0060]

Therefore, including the kinetic energy into the metric **(Fd)**, can enhance the fault-detection, allowing to define in a better way the three operating regions normal/warning/faulty.

[0061]

Several fault-detection algorithms focus only to differentiate between normal and faulty state. However, defining the warning region can also be useful for predictive maintenance purposes as well as to increase the availability and/or to increase mean time between failures of the electromagnetic brake.

[0062]

The fault-isolation section 15, defines three regions, corresponding to: faulty operation, operation under warning and normal operation. Based on these regions – section 15 – it clusters the fault-detection indicator/measure **(Fd)** and displays the status of the electromagnetic brake on the status indicator 16.

[0063]

In addition the fault-isolation section 15 is connected to a gateway 12 via a communication link 11, so remote diagnosis of the electromagnetic brake is possible.

[0064]

Hereby, we mention that the thresholds defining the operation regions including normal, warning and faulty during armature pull-up and release are not the same. The electrical energy required for armature pull-up is higher than the mechanical energy released during armature release. Furthermore, the threshold values between normal/warning/faulty operation regions are application specific and can be decided using interval halving methods. These regions are shown on FIG. 4.

[0065]

Next reference is made to the state-observer, a detailed view of the state-observer 13 which is a piecewise linear observer is shown in FIG. 5.

[0066]

FIG. 5 basically resembles the well-known Luenberger observer (see Non Patent Literature 1). However, the state-space matrices A, B are not constant, since the electromagnetic brake which is an actuator is a nonlinear system. In this case the state-space matrices $\boldsymbol{A} = \boldsymbol{A}(\boldsymbol{i}, \hat{\boldsymbol{z}}), \boldsymbol{B} = \boldsymbol{B}(\boldsymbol{i}, \hat{\boldsymbol{z}})$ are parameter dependent matrices, depending on the detected armature current and estimated armature position. Details about state-observers and piecewise linear observers can be found in Non Patent Literature 2.

[0067]

Furthermore, the design parameter which is the Luenberger vector $\boldsymbol{L} = \boldsymbol{L}(\boldsymbol{i}, \hat{\boldsymbol{z}})$ is also parameter dependent. In FIG. 5, $\hat{y} = \boldsymbol{C}\hat{\boldsymbol{x}}$, and the matrices $\boldsymbol{C} = [\mathbf{1} \quad \mathbf{0} \quad \mathbf{0}]$ and $\mathbf{D} = \mathbf{0}$.

[0068]

The $\boldsymbol{L} = \boldsymbol{L}(\boldsymbol{i}, \hat{\boldsymbol{z}})$ is designed is such a way that the observer is stable and the dynamics fulfills the application dynamic requirements. Using the pole placement algorithm is possible to choose $\boldsymbol{L} = \boldsymbol{L}(\boldsymbol{i}, \hat{\boldsymbol{z}})$ such that the eigenvalues of the $\boldsymbol{A}(\boldsymbol{i}, \hat{\boldsymbol{z}})$-$\boldsymbol{L}(\boldsymbol{i}, \hat{\boldsymbol{z}}) \cdot \boldsymbol{C}$ matrix have negative real part, in this case the observer is stable, for all possible armature current and armature position combinations [1]. As a remark, larger values in the matrix $\boldsymbol{L} = \boldsymbol{L}(\boldsymbol{i}, \hat{\boldsymbol{z}})$ will lead to faster dynamic response but bigger overshoot of the estimate.

[0069]

In the first embodiment of the present invention it was assumed that the spring force (**Fs**) is constant and is known in advance. However, in practice the spring force can go under variation due to settings as well as manufacturing dispersion. Therefore, the second embodiment of the invention is going to overcome this disadvantage.

**[Example 2]**

[0070]

The second embodiment of the present invention is shown in FIG. 6 and in addition to the first embodiment of the present invention it contains an unknown input observer 17, which is used to estimate the spring force.

[0071]

The unknown input observer 17 receives the measured value of the electromagnetic current (**i**) and the applied voltage (**Vin**). Based on these two values section 17 estimates the spring force (**Fs**) and sends it to the state observer, section 13.

[0072]

FIG. 7 is a detailed view of the unknown input observer. The corresponding state-space matrices when the armature is locked into ($\mathbf{z}_0$) initial position are denoted as as $\boldsymbol{A}_l = \boldsymbol{A}_l(\widehat{\imath_l}, \boldsymbol{z}_0)$, $\boldsymbol{B}_l = \boldsymbol{B}_l(\widehat{\imath_l}, \boldsymbol{z}_0)$. The other matrices are $\mathbf{C}_l = \mathbf{1}$ and $\mathbf{D}_l = \mathbf{0}$, so they are not shown explicitly in FIG. 7.

[0073]

Here, the subscript ($l$) denotes that the matrices are related to the model with locked armature.

[0074]

The initial position ($\mathbf{z}_0$) is: ($\mathbf{z}_0 = \mathbf{z}_{\mathbf{min}}$) in case of armature release and ($\mathbf{z}_0 = \mathbf{z}_{\mathbf{max}}$) in case of armature pull-up. The armature release or pull-up operation is uniquely defined by the applied voltage (**Vin**) via section 8 and section 7 as shown in FIG. 1

[0075]

In FIG. 7 the error between the measured current (**i**) and the estimated current ($\widehat{\imath_l}$) is denoted by ($\mathbf{e}_l$).

$$e_l = i - \widehat{\imath_l}$$

[0076]

Here, the subscript ($l$) in the above equation denotes that the estimate is calculated based on the model with locked armature.

[0077]

The armature starts to move when the absolute value of error derivate calculated by section 18 exceeds a certain positive threshold denoted by ε, which is specified by section 19.

[0078]

As a remark, section 18 amplifies the error derivate with a positive constant ($\boldsymbol{k}_\xi$) and also it low-pass filters. The low-pass filter is having a cut-off frequency denoted by ($\boldsymbol{\omega}$).

[0079]

According to FIG. 7, when the armature starts to move, section 19 triggers the switch defined in section 20 as well as section 21 samples and holds the estimated electromagnetic force defined by section 22.

[0080]

Therefore, we can write – when the armature starts to move – the estimated spring force is equal with the estimated electromagnetic force.

$$\widehat{F_S} = F_m(\widehat{\iota_l}, z_0)$$

[0081]

The estimated spring force represents one of the inputs of the state observer 13. After the spring force is estimated the fault detection, fault isolation, status visualization and status data transmission is done according to the first embodiment of this invention.

[0082]

FIG. 8 is an illustrative example of the armature speed (solid line) and estimated speed (dashed line) during armature pull-up and release, when the armature speed and position are estimated according to the method described in the second embodiment of this invention.

[0083]

FIG. 9 is an illustrative example showing the operating regions for a practical case during armature pull-up and release. The asterisks (*) in FIG. 9 relates to real values and the crosses (+) to estimated values. In this example the spring force as well as the armature displacement undergo variations, e.g. due to settings and manufacturing dispersion.

## [Industrial Applicability]

[0084]

The diagnosis device for the electromagnetic brake of this invention is applicable to electromagnetic brakes in many kinds of fields.

## [CLAIMS]

[Claim 1]

A diagnosis device for an electromagnetic brake comprising:

a current detector for detecting a current which flows through an electromagnetic actuator of the electromagnetic brake;

an input voltage detector for detecting applied input voltage on the electromagnetic actuator;

a diagnosis unit for diagnosing the electromagnetic brake status based on detected current and the applied input voltage, having a communication link to a gateway for remote diagnosis.

[Claim 2]

The diagnosis device for the electromagnetic brake according to claim 1, wherein the diagnosis unit comprises:

a state-observer section for estimating moving armature position and speed of the electromagnetic actuator;

a fault-detection section for detecting the armature movement and calculating a fault-detection indicator based on estimated armature displacement and estimated variation of kinetic energy by using an Euclidean norm;

a fault-isolation section for clustering the fault-detection indicator into three predefined regions including normal, warning, and fault;

a status indicator section for visualization of electromagnetic brake status based on performed diagnosis;

wherein the fault-isolation section has the communication link for transmitting the electromagnetic brake status to the gateway.

[Claim 3]

The diagnosis device for the electromagnetic brake according to claim

1, wherein the diagnosis unit comprises:

a unknown input observer section for estimating a spring force of the electromagnetic actuator;

a state-observer section for estimating a moving armature position and speed of the electromagnetic actuator based on detected current, input voltage and estimated spring force;

a fault-detection section for detecting the armature movement and calculating a fault-detection indicator based on estimated armature displacement and estimated variation of kinetic energy by using an Euclidean norm;

a fault-isolation section for clustering the fault-detection indicator into three predefined regions including normal, warning, and fault;

a status indicator section for visualization of electromagnetic brake status based on performed diagnosis;

wherein the fault-isolation section has a communication link for transmitting the electromagnetic brake status to the gateway.

[Claim 4]

The diagnosis device for an electromagnetic brake according to claim 3, wherein the state-observer section uses a locked-armature mathematical model, and the unknown input observer section comprises:

an armature movement detection section;

an electromagnetic force calculation section based on estimated electromagnetic actuator current and moving armature initial position;

a switch section triggered when moving armature movement is detected;

a sample and hold section for sampling and holding the estimated electromagnetic force, which equals the spring force when the moving armature starts to move.

[Claim 5]

The diagnosis device for an electromagnetic brake according to one of claims 1 to 4, wherein the electromagnetic brake is provided in an elevator.

FIG.1

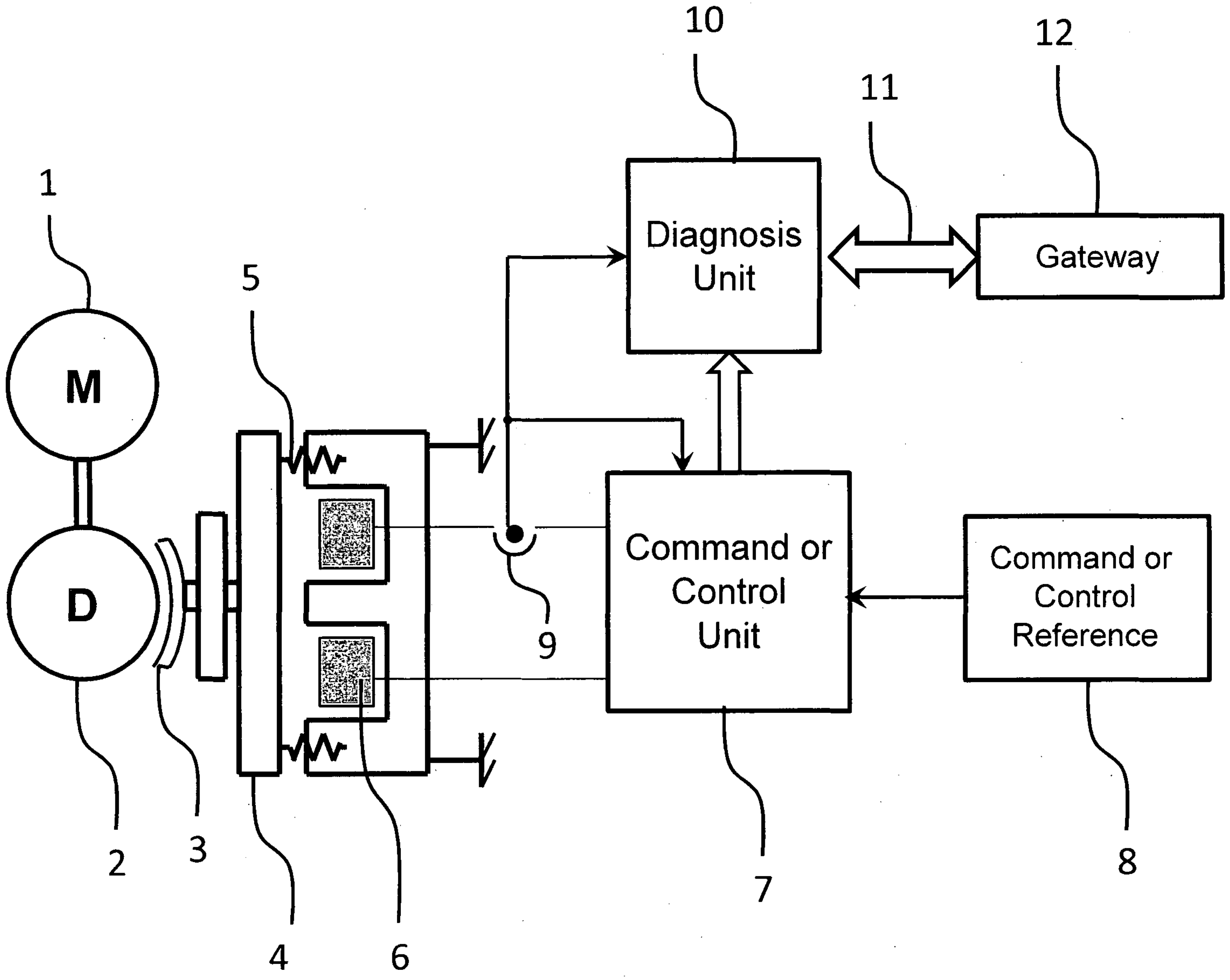

10
12
11
1
Diagnosis
Unit
Gateway
5
M
D
Command or
Control
Unit
Command or
Control
Reference
9
2
3
7
8
4
6

FIG.2

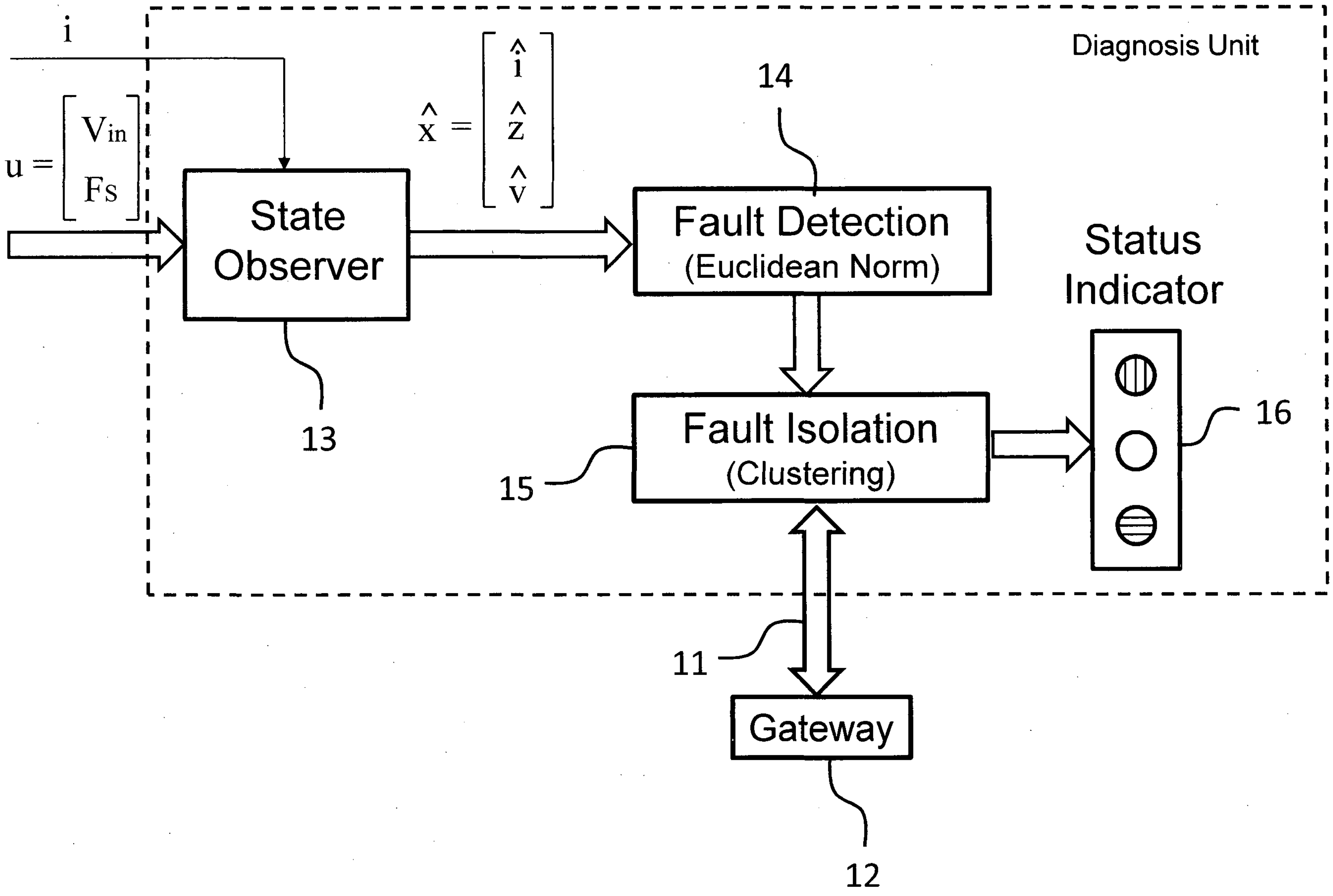

i
$u = \begin{bmatrix} V_{in} \\ F_S \end{bmatrix}$
State Observer
13
$\hat{x} = \begin{bmatrix} \hat{i} \\ \hat{z} \\ \hat{v} \end{bmatrix}$
Diagnosis Unit
14
Fault Detection
(Euclidean Norm)
Status Indicator
16
Fault Isolation
(Clustering)
15
11
Gateway
12

FIG.3

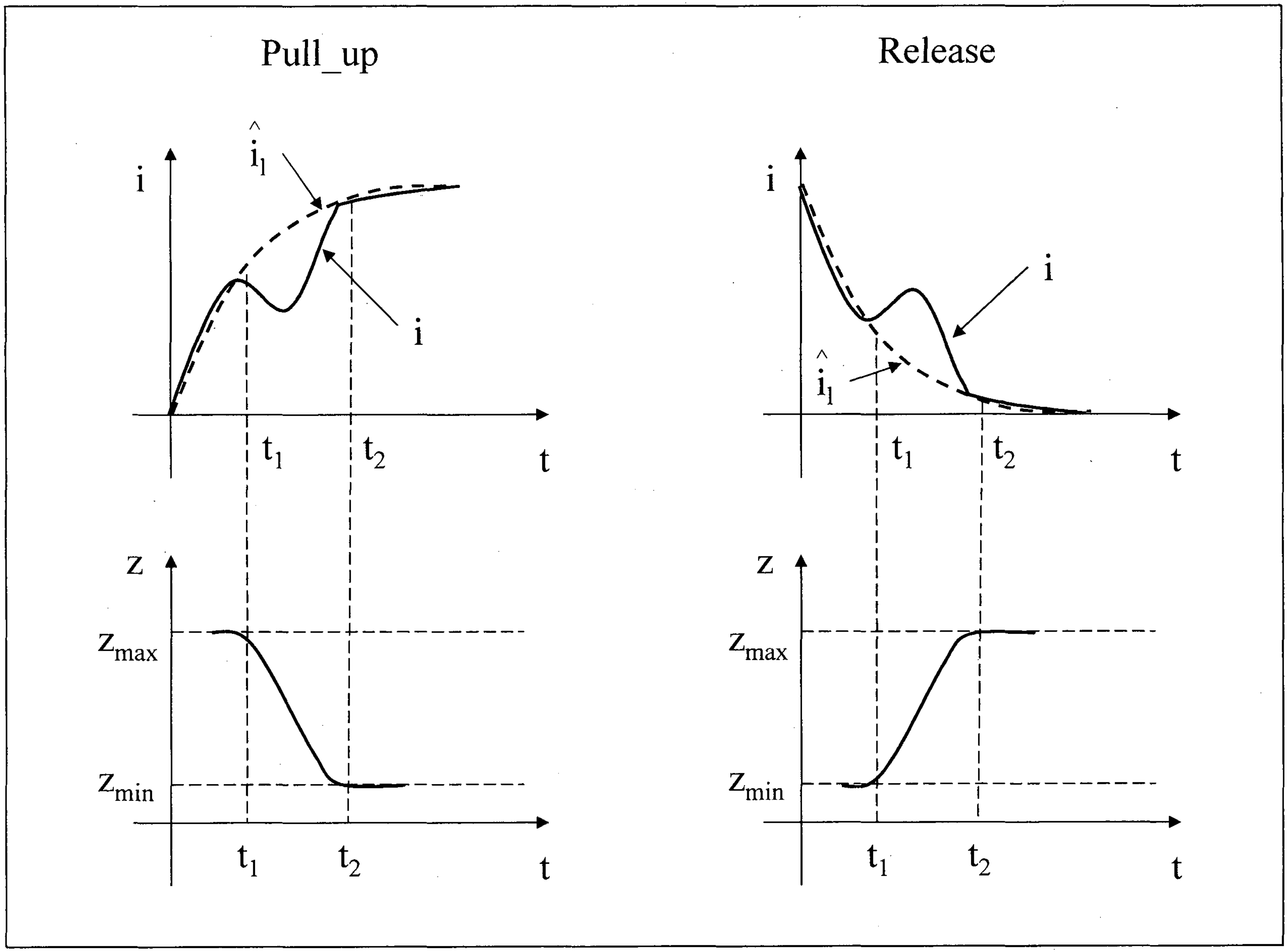


FIG.4

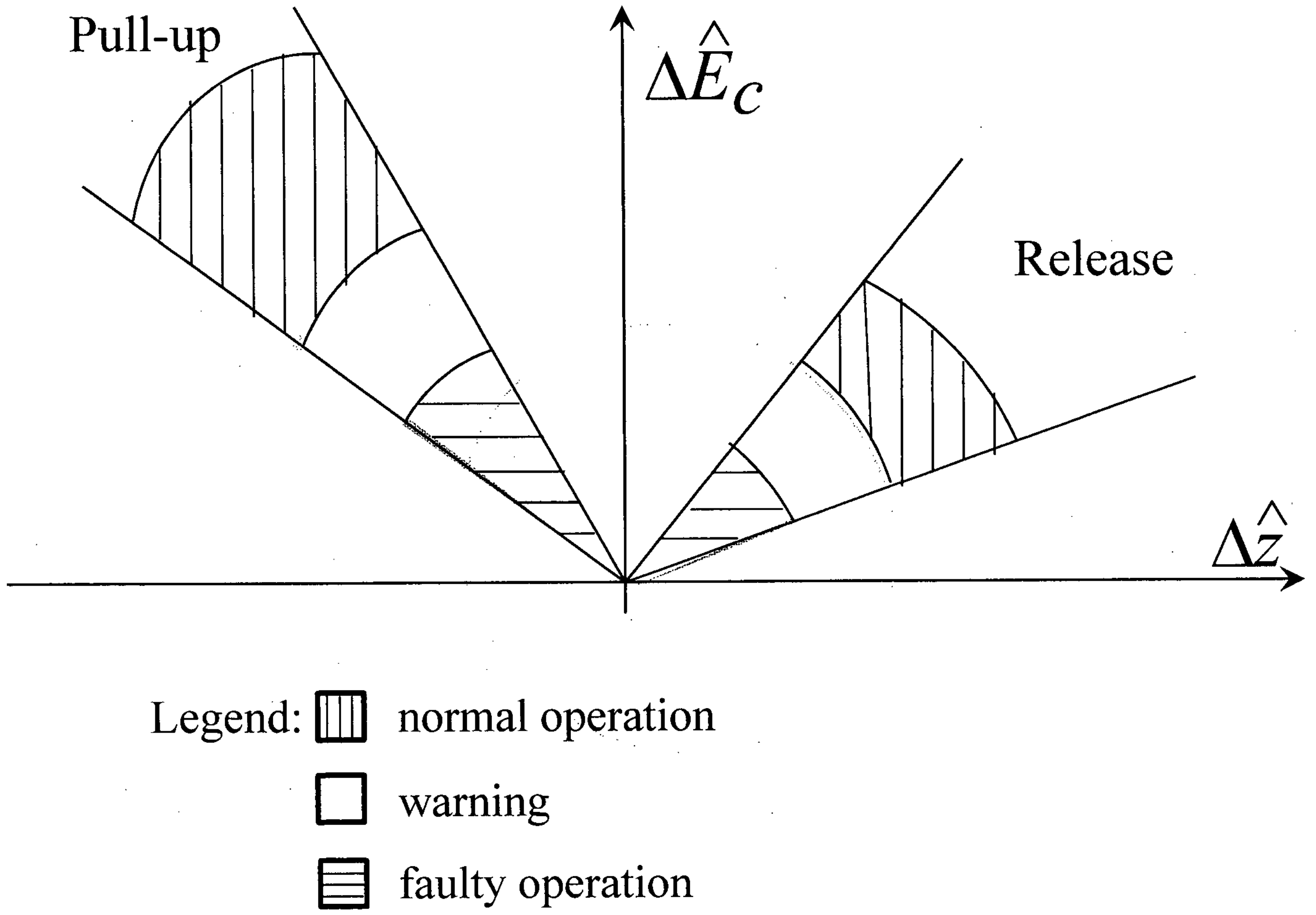

Pull-up
$\Delta\hat{E}_c$
Release
$\Delta\hat{z}$
Legend: ▥ normal operation
☐ warning
▤ faulty operation

FIG.5

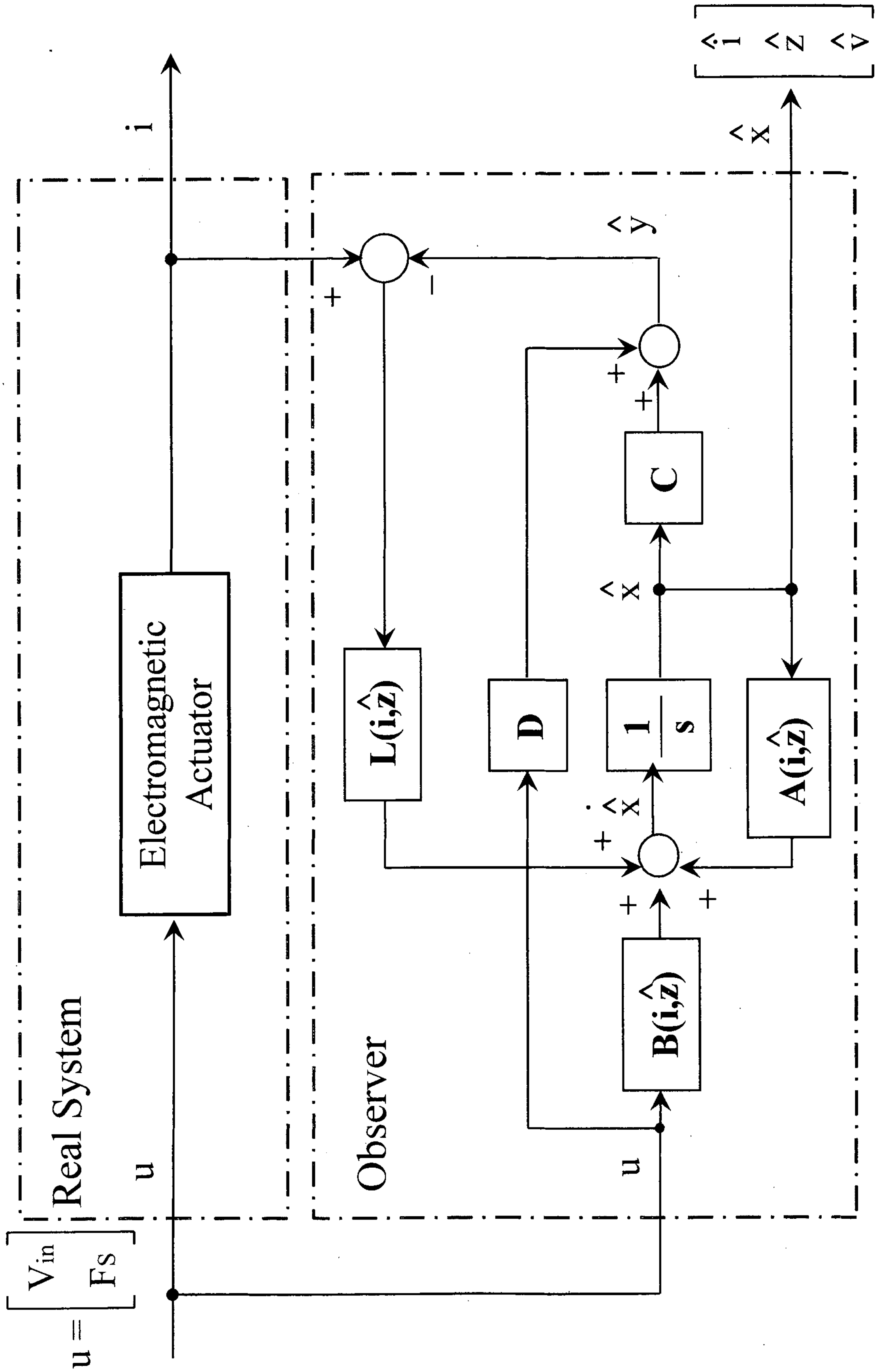

$u = \begin{bmatrix} V_{in} \\ F_S \end{bmatrix}$
Real System
u
Electromagnetic Actuator
i
Observer
u
$B(i,\hat{z})$
D
$L(i,\hat{z})$
+
−
+
+
+
$\dot{\hat{x}}$
+
+
$\frac{1}{s}$
$\hat{x}$
C
$\hat{y}$
$A(i,\hat{z})$
$\hat{x}$
$\begin{bmatrix} \hat{i} \\ \hat{z} \\ \hat{v} \end{bmatrix}$

FIG.6

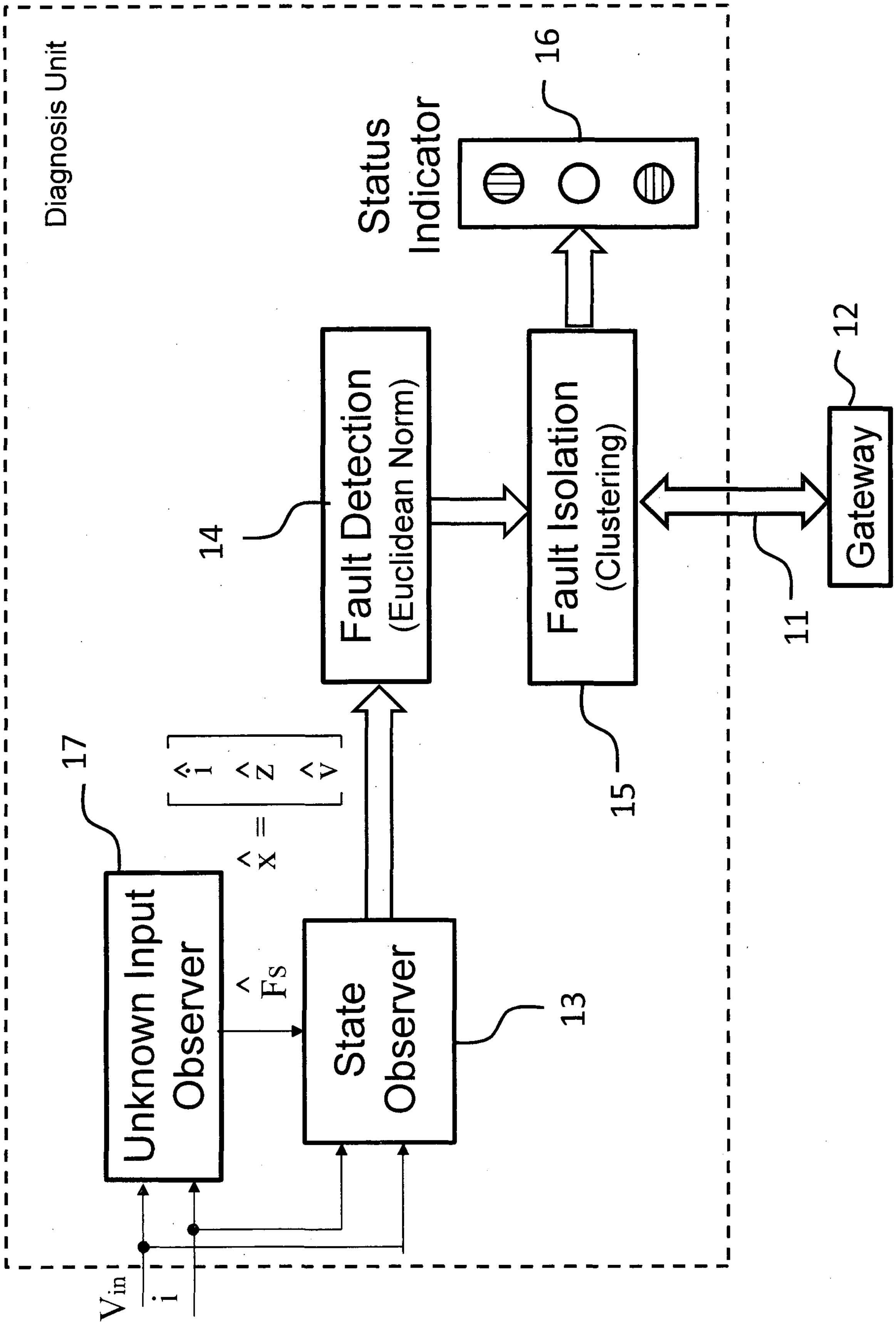

Diagnosis Unit
Unknown Input Observer
17
$\hat{F}_S$
State Observer
13
$\hat{x} = \begin{bmatrix} \hat{i} \\ \hat{z} \\ \hat{v} \end{bmatrix}$
Fault Detection
(Euclidean Norm)
14
Fault Isolation
(Clustering)
15
Status Indicator
16
Gateway
12
11
$V_{in}$
$i$

FIG.7

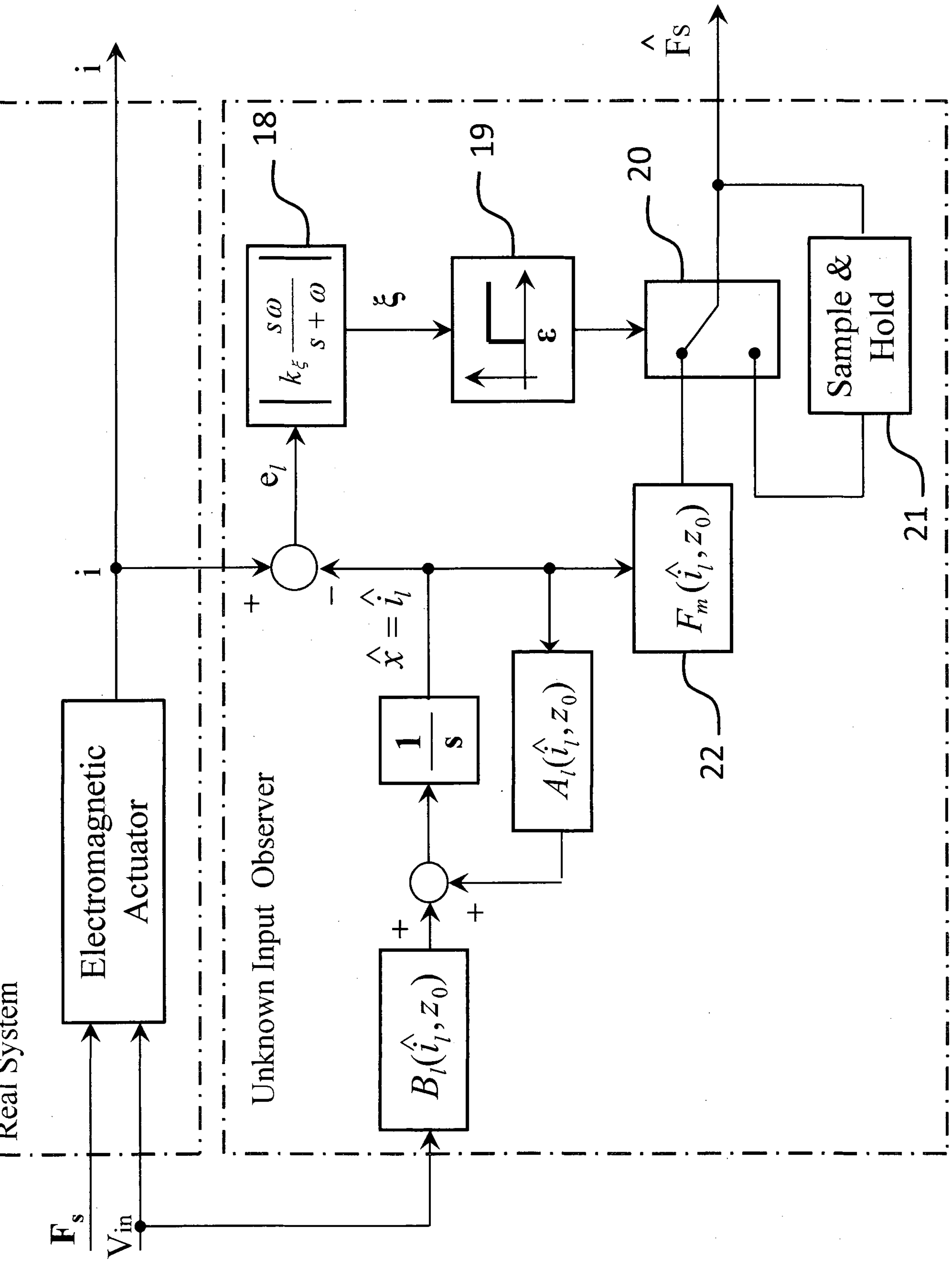
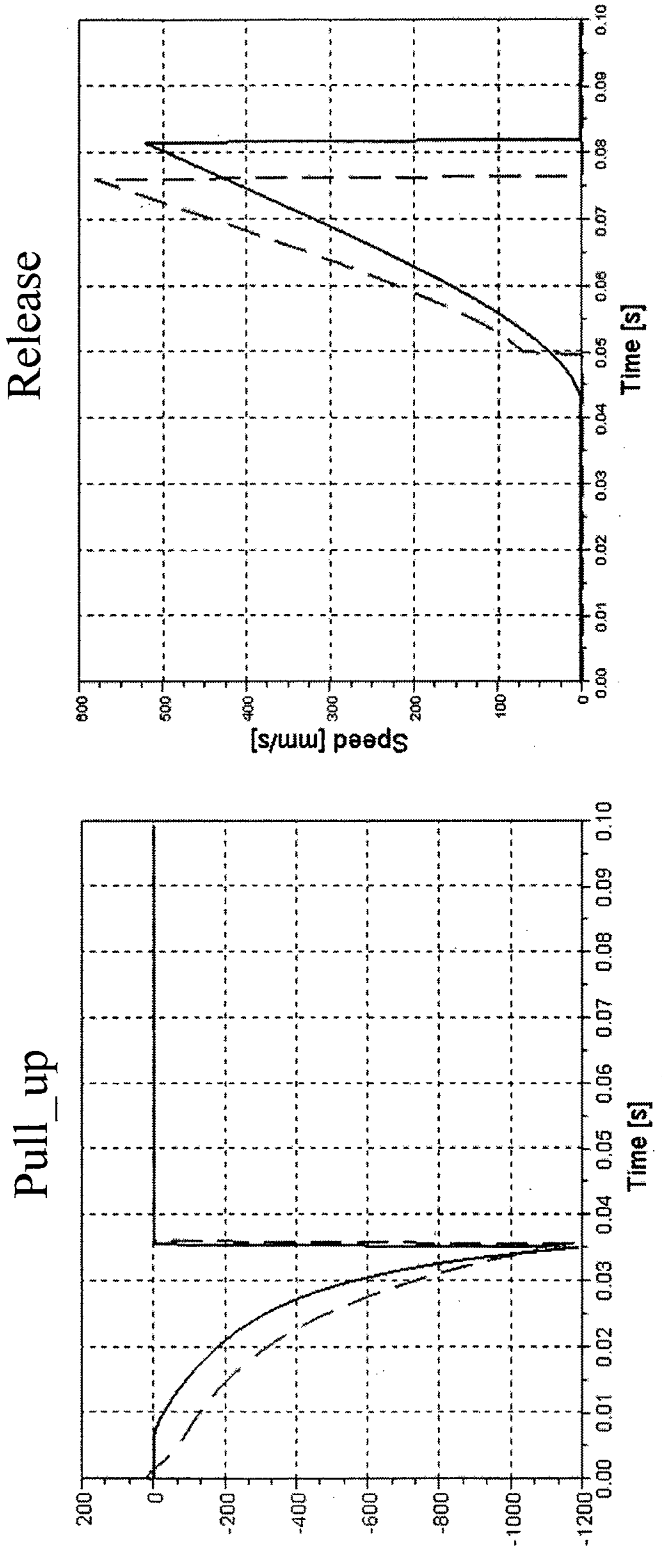

Real System
Electromagnetic Actuator
$\mathbf{F}_s$
$V_{in}$
i
i
Unknown Input Observer
18
19
20
21
22
$e_l$
$k_\xi \left| \frac{s\omega}{s+\omega} \right|$
$\xi$
$\varepsilon$
+
−
$\hat{x} = \hat{i}_l$
$\frac{1}{s}$
$B_l(\hat{i}_l, z_0)$
$A_l(\hat{i}_l, z_0)$
$F_m(\hat{i}_l, z_0)$
+
+
Sample & Hold
$\hat{F}s$

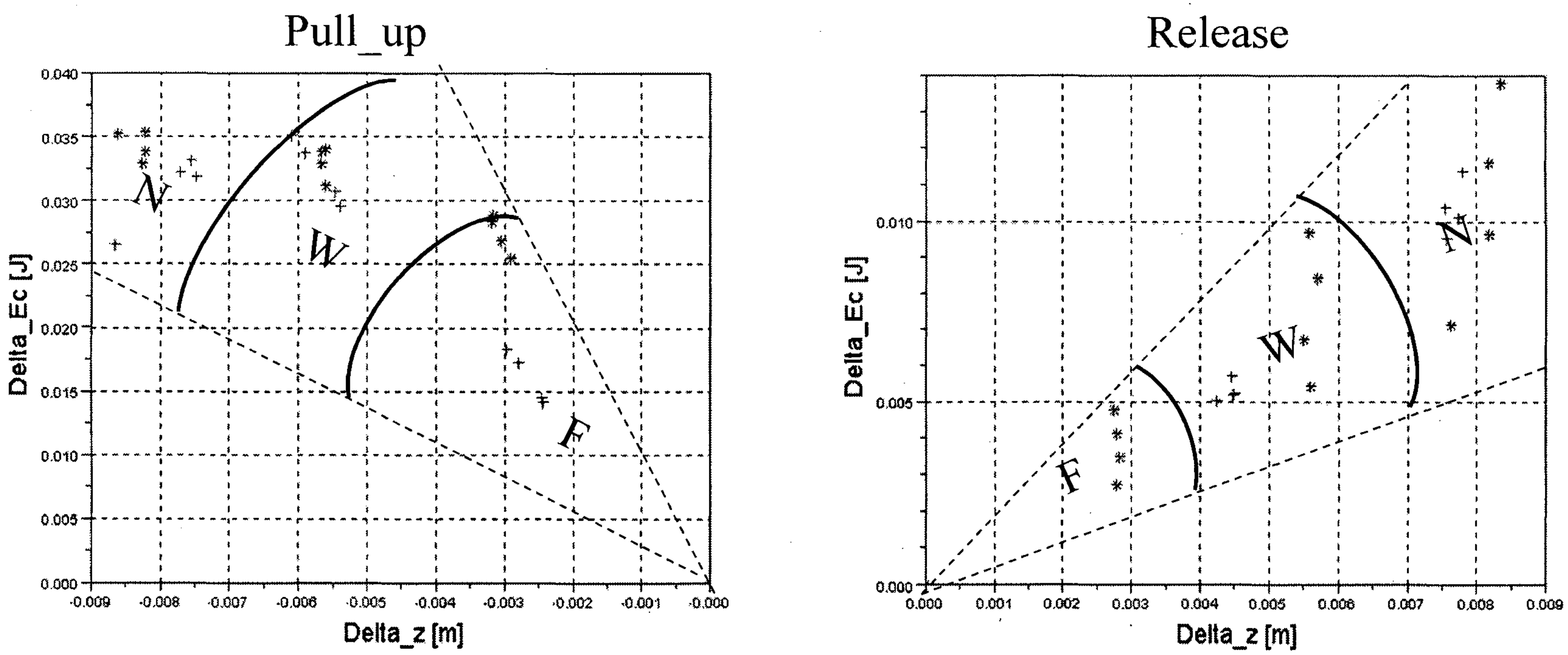
FIG.8



Pull_up

Release

FIG.9



Legend: N normal operation
W warning
F faulty operation

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2016/084867

## A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. B66B5/02(2006.01)i, B66B11/08(2006.01)i, F16D65/18(2006.01)i,
F16D121/22(2012.01)n

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)

Int.Cl. B66B5/02, B66B11/08, F16D65/18, F16D121/22

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2017
Registered utility model specifications of Japan 1996-2017
Published registered utility model applications of Japan 1994-2017

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. |
|---|---|---|
| X<br>A | JP 6-107387 A (HITACHI BUILDING SYSTEM SERVICE CO.,LTD.) 1994.04.19, paragraphs [0008] - [0015] ,Figs.1-2 (No Family) | 1,5<br>2-4 |
| A | JP 2007-84177 A (TOSHIBA ELEVATOR CO.,LTD.) 2007.04.05, paragraphs [0013] - [0022] ,Figs.1-2 (No Family) | 1-5 |
| A | JP 61-287684 A (HITACHI ELEVATOR SERVICE CO.,LTD.) 1986.12.18, claim 1 (No Family) | 1-5 |
| A | US 2015/0053507 A1 (KONE CORPORATION) 2015.02.26, paragraphs [0039] - [0043] ,Fig.1 & CN 104364177 A | 1-5 |

☑ Further documents are listed in the continuation of Box C. ☐ 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
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

| | |
|---|---|
| Date of the actual completion of the international search<br>17.02.2017 | Date of mailing of the international search report<br>28.02.2017 |
| Name and mailing address of the ISA/JP<br>**Japan Patent Office**<br>3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan | Authorized officer 3W 3524<br>TAKEMURA, Hideyasu<br>Telephone No. +81-3-3581-1101 Ext. 3367 |

**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/JP2016/084867

| C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT | | |
|---|---|---|
| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
| A | JP 2010-84930 A (GKN DRIVELINE JAPAN LTD.) 2010.11.24, paragraphs [0023] - [0025] ,Fig.1 (No Family) | 4-5 |