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**US-A1- 2010 140 938**  
**VAN DER HOOFT E L ET AL: "Wind turbine control algorithms", ECN LITERATURE REVIEW, XX, XX, Bd. ECN-C-03-111, 1. Dezember 2003 (2003-12-01), Seiten 1-89, XP003008410,**



The present invention relates to a method for operating a pitch-controlled wind turbine, in which a setpoint value  $M$  for the generator torque is specified depending on a rotational speed  $n$  of the generator or rotor. The allocation rule for the setpoint value  $M$  depending on the rotational speed  $n$  has a transition point, in which a transition takes place from a partial load operation to a rated load operation. In the rated load operation, a regulation of the rotational speed  $n_3$  at a setpoint value  $M_3$  takes place from the transition point through an adjustment of the blade pitch angle.

A method for controlling a wind turbine with an electrical generator using air density data at the site of the wind turbine is known from DE 101 09 553 B4. In the method, the generator of the wind turbine is controlled by means of a control device, which processes the air density data, and power data from the generator is adjusted depending on the air density. In the known method, the height of the installation location of the wind turbine above sea level is taken into consideration, wherein the lower air density is taken into consideration in the power curve. The power assigned to a rotor rotational speed and thus to a certain tip speed ratio to be generated by the wind turbine can thereby be appropriately adjusted, i.e. decreased, so that the generator torque does not exceed the torque made available via the generator as a result of an exciter power fed in by the control device. Overall, the efficiency determined via the power curve should be retained and the maximum energy should be taken from the wind.

A method for calculating a power curve for elevated locations is known from EP 1 939 445 A2. Starting from a relationship between the power coefficients  $c_P$  and the tip speed ratio  $\lambda$ , a ratio is here determined between the electrical output power  $P$  and the wind speed  $v$ .

A wind turbine is known from EP 1 918 581 A2, in which the output power is reduced when the temperature of the ambient air drops below a predetermined threshold value. The background for the power reduction is that the operation of the wind turbine can require other load calculations at temperatures of below  $-20^\circ\text{C}$ .

An optimization method for the operation of a wind turbine in full load operation is known from E.L. van der Hooft et al. "Wind turbine control algorithms," ECN Literature

Review Bd. ECN-C—03-111. Within the framework of the optimization method, curves of constant power are considered.

A method for operating a wind turbine is known from DE 10 2009 025 445 B3, in which a meteorological value is captured and, taking the measured value into consideration, a  
5 setpoint value for the system operation is specified. In this case, the measured value is an air mass flow caused by the wind.

In the case of the effects of the air density on the output of the wind turbine, it should be taken into consideration that, in the case of pitch-controlled wind turbines, a change in the air conditions can lead to aerodynamic stall effects with an undesired stall.

10 The object of the invention is to provide an improved method for operating a pitch-controlled wind turbine, in which the falling air density is taken into consideration in the specification of the setpoint value for the generator torque and undesired stall effects at the rotor blade are simultaneously avoided.

According to the invention, the object is solved by a method with the features from claim  
15 1. Advantageous embodiments form the subject matter of the dependent claims.

In the case of the method according to the invention, the operation of a pitch-controlled wind turbine, in which a setpoint value  $M$  for the generator torque is assigned to an actual value of a rotational speed  $n$  of the generator or of the rotor, takes place.

Generally, in the case of the operation of the wind turbine, we differentiate between a  
20 partial load operation and a rated load operation. In partial load operation, the setpoint value for the generator torque increases with an increasing rotational speed. In rated load operation, a regulation of the rotational speed  $n_3$  takes place through the adjustment of the blade adjustment angle at a setpoint value  $M_3$ .

The transition from partial load operation to rated load operation takes place at a  
25 transition point, which is defined by a value for the rotational speed  $n_3$  and a setpoint value for the generator torque  $M_3$ . According to the invention, the values of the transition point are determined depending on a current value of the air density, wherein the rotational speed  $n_3$  increases with a falling air density and/or the setpoint value for the generator torque  $M_3$  is reduced. It can hereby be ensured that the wind turbine can

continue to work economically and without problems with a stable regulation at a higher rotational speed and lower generator torque at a falling air density. The rated load operation then takes place in the case of the method according to the invention with the reduced generator torque  $M_3$  from the transition point. Undesired aerodynamic stall effects can be avoided through the adjustment of the rotational speed  $n_3$ , as of which the rated load operation takes place.

According to the invention, the current air density  $\rho$  is determined depending on the measured air temperature  $T$  and an air pressure  $p$  taking into consideration a value for the air humidity  $\psi$ . The relative air humidity can have a significant impact on the air density in particular in the case of the installation of the wind turbines at locations with a high ambient temperature, where the air can accommodate a lot of humidity, and on mountains or hills, where clouds, fog and the like can be expected. According to the invention, the value  $\psi$  for the air humidity is specified depending on a time of day or time of year.

In order to even better avoid undesired stall effects, an adjustment of the blade pitch angle to a minimum blade pitch angle already preferably takes place in partial load operation. The rotor blade then transitions to rated load operation specified by the air density with a minimum blade pitch angle.

In the preferred embodiment, the transition from partial load operation to rated load operation for the wind turbine varies depending on the air density. At the same time, a "pre-pitching" of the rotor blade in partial load operation takes place so that the rotor blade does not take the maximum possible power from the wind when entering rated load operation.

In a preferred further development of the method according to the invention, the value of the minimal blade pitch angle is also selected depending on the air density. In this manner, it can be determined with which minimum blade pitch angle the rotor blade enters rated load operation.

In a preferred embodiment, a predetermined break point ( $n_2$ ,  $M_2$ ) is provided during the allocation of the setpoint value for the generator torque, as of which a linear increase in the setpoint value for the generator torque takes place up to the rated load operation.

This predetermined break point generally marks the transition from an area, in which an optimal specification of the setpoint value for the torque takes place depending on the rotational speed and the power coefficient of the rotor blade, and an area, in which a rapid increase in the setpoint value for the generator torque at an increasing rotational speed results.

In a preferred embodiment, the setpoint value  $M_2$  for the generator torque at a constant rotational speed  $n_2$  decreases with decreasing air density. This approach is consistent with the idea that the ideal power consumption of the rotor is proportional to the air density so that with falling air density, less optimal performance can be received with the rotor blade. Thus, for the break point  $(n_2, M_2)$ , the transition to the linear increase with decreasing air density is also shifted to lower setpoint values for the generator torque.

A preferred exemplary embodiment is explained in greater detail below based on the figures. They show in:

Fig. 1 the characteristic line for the setpoint value of the generator torque depending on the generator rotational speed,

Fig. 2 a flow diagram for calculating the rotational speed change and the setpoint value change for the generator torque depending on the air temperature, the air pressure and the air humidity,

Fig. 3 the characteristic line for the setpoint value of the generator torque depending on the generator rotational speed with its displaced progression in the case of a sinking air density, and

Fig. 4 the progression of the blade pitch angle depending on the generator speed.

Fig. 1 shows as an example the progression of a characteristic line, which shows the setpoint value of the generator torque  $M_{Gen}$  depending on the generator rotational speed  $n_{Gen}$ . Here, the characteristic line distinguishes four sections. In a first section, a linear increase of the setpoint value takes place for the generator torque  $M_{Gen}$  with increasing generator rotational speed  $n_{Gen}$ .

In a second section 12, the characteristic line of the ideal characteristic line of the rotor follows. The setpoint value for the generator torque is calculated via a function for the optimum power  $P_{opt}$ , which is as follows:

$$P_{opt}(n) = \left( 2 * \pi * R * \frac{n}{\dot{U}_{Getr}} * \frac{1}{60 * \lambda_{opt}} \right)^3 * \pi * R^2 * \frac{\rho}{2} * c_{p_{opt}}$$

- 5 wherein R is the radius of the rotor, n the generator rotational speed,  $\dot{U}_{Getr}$  the transmission ratio of the gearbox,  $\lambda_{opt}$  the optimal tip speed ratio of the rotor blade,  $\rho$  the air density and  $c_{p_{opt}}$  the optimal power coefficient. Along section 12 of the characteristic line, the setpoint value for the generator torque is calculated analytically according to the above formula.
- 10 In point 14, a break point is present between the second section 12 and a third section 16 of the characteristic line. With section 16, the ideal characteristic line 12 is left in order to achieve optimum energy efficiency and the setpoint value for the generator torque increases more intensely with the increasing speed of the generator. In the exemplary embodiment shown, the characteristic line section 16 is shown as a linearly
- 15 increasing section. Other non-linear shapes of the increase between the break point 14 and a transition point 18 are also possible. At transition point 18, the wind turbine transitions to its rated load operation. In this area, it is imperative that the power of the wind turbine is held constant, wherein the power P is proportional to the rotational speed and the torque of the generator:

$$P = M * \omega$$

20

wherein  $\omega = 2 \pi n_{Gen}$  is the angular frequency of the generator.

Fig. 2 describes in a flow diagram how the rotational speed and the setpoint value of the torque change at transition point 18 depending on the air density. For this, in a method step 24, an air density  $\rho_0$  is calculated for sea level, starting from the ambient

25 temperature  $T_0$ , which specifies the air temperature of the surroundings at sea level, an

air pressure  $p_0$ , which specifies the air pressure at sea level, and a value for the air humidity  $\psi_0$ , which specifies the air humidity at sea level.

The calculation of the air density including the air humidity takes place in a generally known manner.

- 5 On the wind turbine, the air temperature at operating point  $T_1$  as well as the air pressure at operating point  $p_1$  are captured by sensors in step 26. A value for the air humidity  $\psi_1$  at the operating point is made available either per parameter specification from a data source 30 or based on a predetermined time function 32. A parameter for the air humidity at operating point  $\psi_1$  can be determined for example seasonally or specified  
10 depending on the time of day.

The values for air temperature, air pressure and air humidity are available in method step 34 for the operating point of the wind turbine and are converted into an air density for the current operating point  $p_1$  in step 36. Just like in step 24, the calculation of the air density in step 36 also takes place in a known manner.

- 15 A change in the air density  $\Delta\rho$  is determined in method step 38. The difference of the air density  $\Delta\rho$  results from the air density calculated in step 24 for sea level  $\rho_0$  and from the air density calculated in step 36 for the current operating point  $p_1$ . It is checked in a subsequent method step 40 whether the change in the air density  $\Delta\rho$  exceeds a maximum value for the change in the air density  $\Delta\rho_2$ . In the event that the determined  
20 change in the air density  $\Delta\rho$  exceeds the maximum permissible change in the air density  $\Delta\rho_2$  in method step 40, a change in the generator rotational speed  $\Delta n$  and a change in the generator torque  $\Delta M$  are calculated in a subsequent step 42. The calculation in step 42 is made as follows:

$$\Delta n = x \Delta n(n_2) + \Delta n_0$$

$$\Delta M = y \Delta M(n_2) + \Delta M_0,$$

- 25 wherein  $x$ ,  $y$  are parameterizable constants,  $\Delta M(n_2)$  is the change in the setpoint value for the generator torque at rotational speed  $n_2$  and  $\Delta n_0$  as well as  $\Delta M_0$  are system-specific constants. In order to calculate  $\Delta M(n_2)$ , the rotational speed for  $n_2$  is selected in

the break point in which the characteristic line from the second section 12 transitions into the steeply increasing third section 16 of the characteristic line. The advantage of this definition for  $\Delta M$  ( $n_2$ ) is that the value can be calculated analytically as the end point of the second section.

- 5 In addition to the determination of the values  $\Delta n$  and  $\Delta M$  in step 42, a value  $\Delta \psi$  for the blade pitch angle is also calculated in step 44, which is dependent on the air density  $\rho_1$  in the operating point, which was determined in step 36.

If it is determined upon query in step 40 that the change in the air density  $\Delta \rho$  calculated in method step 38 is less than the maximum permissible change in the air density  $\Delta \rho_2$  or  
 10 equal to the maximum permissible change in the air density  $\Delta \rho_2$ , the method returns again to method step 34 via the branch 46 in order to recalculate a value of the air density in the operating point  $\rho_1$ .

Fig. 3 shows a change in the characteristic line in the case of decreasing air density. The transition point 18 is clearly shifted to a new transition point 48. If the method for  
 15 correcting the characteristic line is taken into consideration, it can also be understood as an autocorrected control function. The shift in the transition point means:

$$(n_3, M_3) \rightarrow (n_3 + \Delta n, M_3 - \Delta M),$$

wherein  $n_3$  and  $M_3$  indicate the transition point 18 of the non-shifted characteristic line and  $n_3 + \Delta n$  designate the rotational speed of the shifted transition point and  $M_3 - \Delta M$   
 20 the setpoint value of the generator torque of the shifted transition point.

One important aspect of the above shift in the transition point is that in this case, not only a reduction in the setpoint value for the generator torque does take place but rather an increase in the rotational speed is also simultaneously provided as of which the wind turbine switches to rated load operation. The section of the characteristic line, which  
 25 designates the rated load operation during reduced air density, is shown tied in with the transition point 48 as characteristic line 50. As noted in Fig. 3, the change in the transition point 18 up to the new transition point 48 is dependent on the temperature, the air pressure and the air humidity.

As further shown in Fig. 3, a maximum generator rotational speed  $n_4$  can be defined for the generator depending on the construction. If the new rotational speed  $n_3 + \Delta n$  resulting starting from the transition point 18 is greater than the maximum permissible value for the generator rotational speed  $n_4$ , then the rotational speed is not increased further but rather an increase in the rotational speed takes place only up to the maximum permissible generator rotational speed. In this example, the reduction in the setpoint value of the generator torque can also still be adjusted by  $\Delta M$  starting from the transition point 18. One option for the adjustment is given by the boundary condition that:

$$(\nabla u)_s + (\nabla W)_s = \text{constant.}$$

This means that, starting from the transition point 18, an increase in the generator rotational speed for the new transition point 48 takes place only up to the maximum permissible generator speed  $n_4$ . On the other hand, the decrease in the setpoint value for the generator torque takes place when the distance between the transition points 18 and 48 resulting in the case of an unrestricted increase in the rotational speed is held at a constant level. Here, the decrease in the setpoint value for the generator torque thereby takes place along an imaginary circle, the middle point of which forms the transition point 18 and the radius of which is determined to be

$$\sqrt{(\Delta n)^2 + (\Delta M)^2}$$

In the shift in the transition point described above for the rated operation during decreasing air density, the other characteristic line sections also change. As directly results from the formula described further above, the characteristic line section 12 is proportional to the air density so that the second characteristic line section 12 shifts overall towards smaller setpoint values for the generator torque. The changed characteristic line section 52 also means that the break point 14 for the abandoning of the second characteristic line section shifts overall towards smaller setpoint values for the generator torque. The shifted break point 54 is characterized in that only the setpoint value for the generator torque is reduced based on the characteristic line

section 52, but not the value for the rotational speed. The shifted break point 54 and the shifted transition point 48 lead to a third characteristic line section 56, which progresses flatter than the third characteristic line section 16.

5 The lowering of the second characteristic line section 12 for the first characteristic line section 10 also results in a flatter progression, which is shown by characteristic line section 58.

10 Fig. 4 shows the progression of the minimum blade pitch angle depending on the rotational speed. Fig. 4 a shows the conventional operation of a wind turbine according to the prior art. For the wind turbine, in normal operation, the minimum blade pitch angle up to a rotational speed of  $n_1$  is restricted by the line 60. Only after transition to the rated load operation at rotational speed  $n_3$ , a restriction of the minimal blade pitch angle takes place through curve 62, which increases linearly.

Here, the diagram should be read such that the minimum permissible blade pitch angle is specified depending on the generator rotational speed.

15 In the case of the method according to the invention, which is shown in Fig. 4 b, a specification of a minimum permissible blade pitch angle already takes place as of a rotational speed  $n_2$ . A minimum blade pitch angle according to the curve section 68 is thus specified even before a transition to rated load operation at the speed  $n_3$ . In rated load operation, a specification of the minimum blade pitch angle according to curve section 70 is made, wherein the minimum blade pitch angle according to curve section 20 70 is greater than in the curve section 62.

In the exemplary embodiment shown according to Fig. 4b, an air-density-dependent adjustment of the minimum blade pitch angle does not take place for the sound-reduced operation so that the curve 62 is substantially unchanged.

**Patentkrav**

1. Fremgangsmåde til drift af en pitchstyret vindturbin med en rotor og en generator, i hvilken en ønsket værdi for generatorens drejningsmoment ( $M$ ) forudindstilles afhængigt af rotationshastigheden ( $n$ ) af generatoren eller rotoren,
- 5 hvorved et overgangspunkt ( $n_3, M_3$ ) tilvejebringes, ved hvilket en overgang fra en drift med delbelastning til en drift med nominel belastning finder sted, hvor en styring af rotationshastigheden sker ved justering af vinklen af hældningen af bladet med en ønsket værdi ( $M_3$ ) fra overgangspunktet,
- kendetegnet ved, at**
- 10 • en faktisk værdi af densiteten af luften ( $\rho$ ) beregnes, og
- værdierne ( $n_3, M_3$ ) ved overgangspunktet bestemmes afhængigt af den faktiske værdi af densiteten af luften ( $\rho$ ), hvorved rotationshastigheden ( $n_3$ ) øges og/eller den ønskede værdi for generatorens drejningsmoment ( $M_3$ ) reduceres, når densiteten af luften ( $\rho$ ) falder, hvilken faktiske densitet af luften ( $\rho$ ) bestemmes
- 15 afhængigt af en målt temperatur af luften ( $T$ ) og et målt tryk af luften ( $p$ ) under hensyntagen til en værdi af luftfugtigheden ( $\Psi$ ), som forudindstilles afhængigt af tidspunktet på dagen og/eller årstiden.
2. Fremgangsmåden ifølge krav 1, **kendetegnet ved, at** en justering af vinklen af hældningen af bladet til en minimum vinkel af hældningen af bladet udføres allerede under driften med delbelastning.
3. Fremgangsmåden ifølge krav 2, **kendetegnet ved, at** værdien af den minimale vinkel af hældningen af bladet vælges afhængigt af densiteten af luften ( $\rho$ ).
- 25
4. Fremgangsmåde ifølge et hvilket som helst af kravene 1 til 3, **kendetegnet ved, at** den karakteristiske linje har et forudindstillet punkt ( $n_2, M_2$ ), hvorfra en lineær forøgelse af den ønskede værdi for generatorens drejningsmoment finder sted op til driften med nominel belastning.

5. Fremgangsmåden ifølge krav 4, **kendetegnet ved, at** den ønskede værdi for generatorens drejningsmoment ( $M_2$ ) reduceres, når densiteten af luften ( $\rho$ ) falder ved uændret omdrejningshastighed ( $n_2$ ).

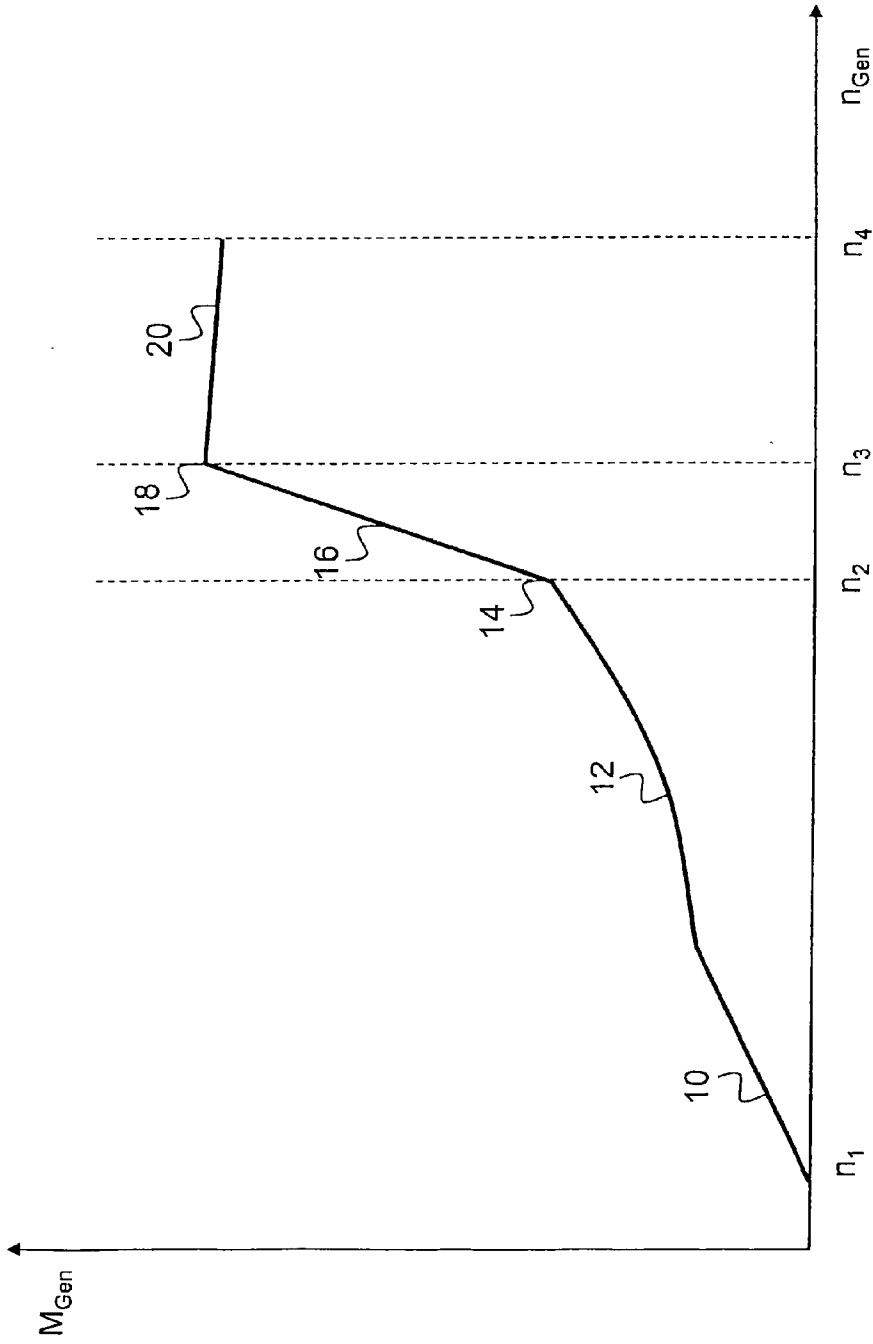


Fig. 1

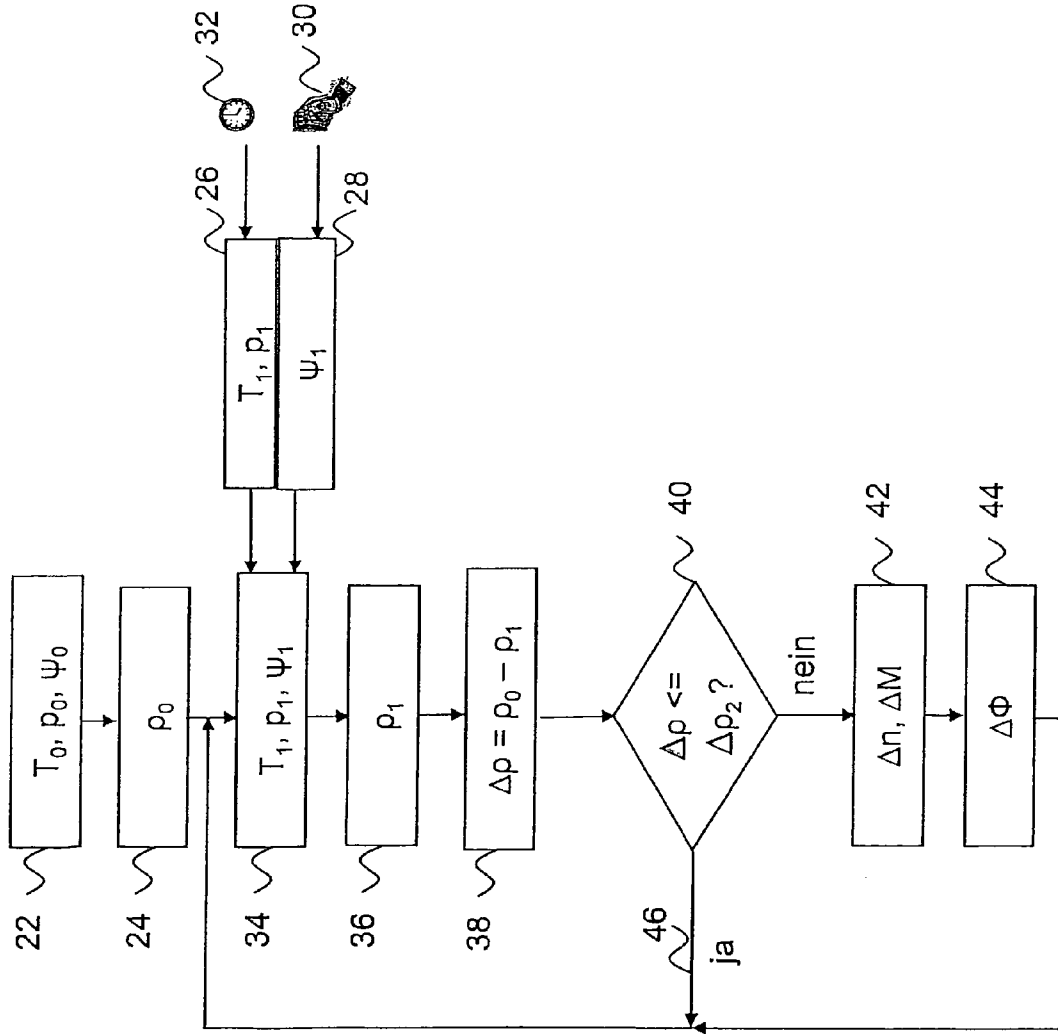


Fig. 2

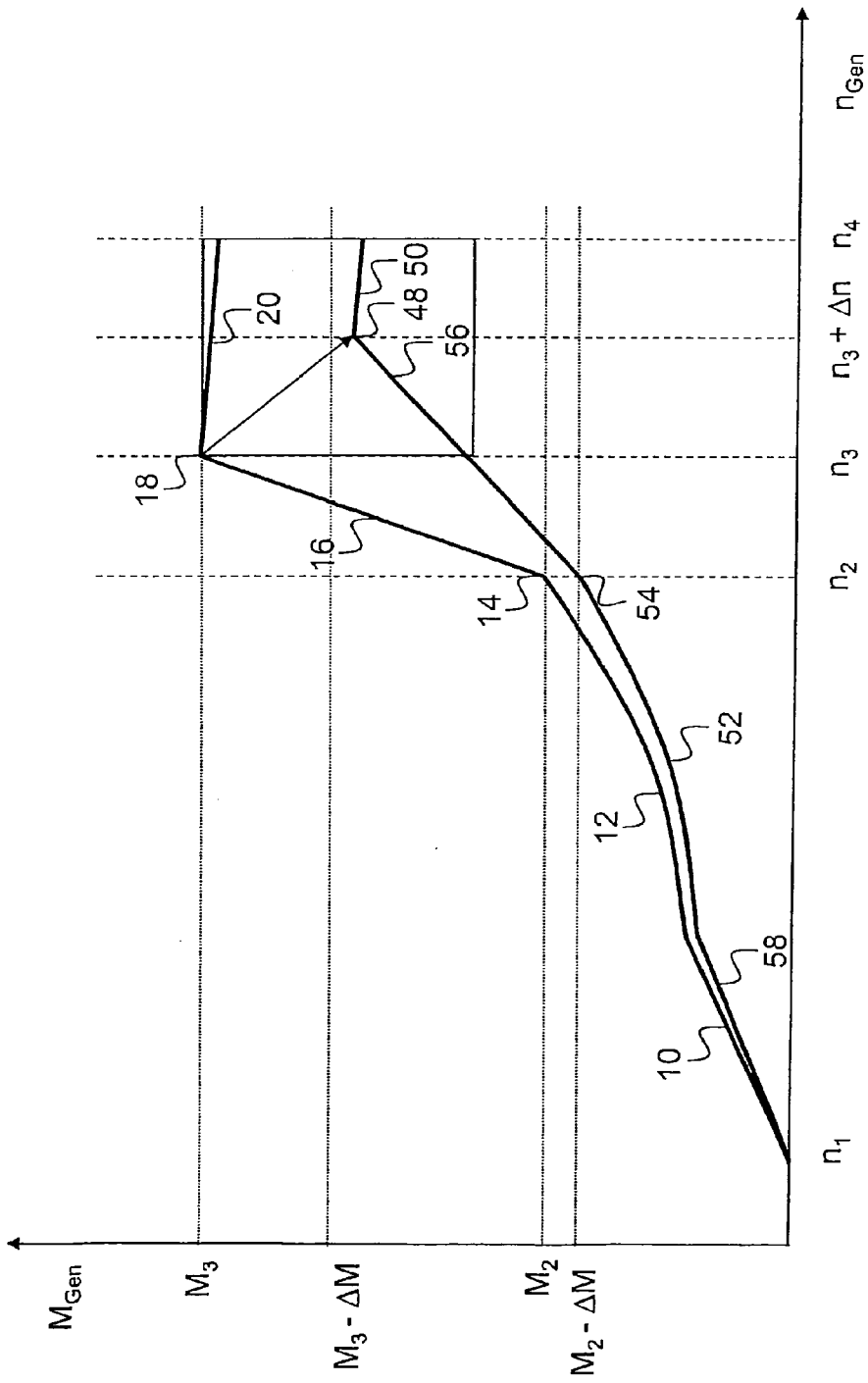


Fig. 3

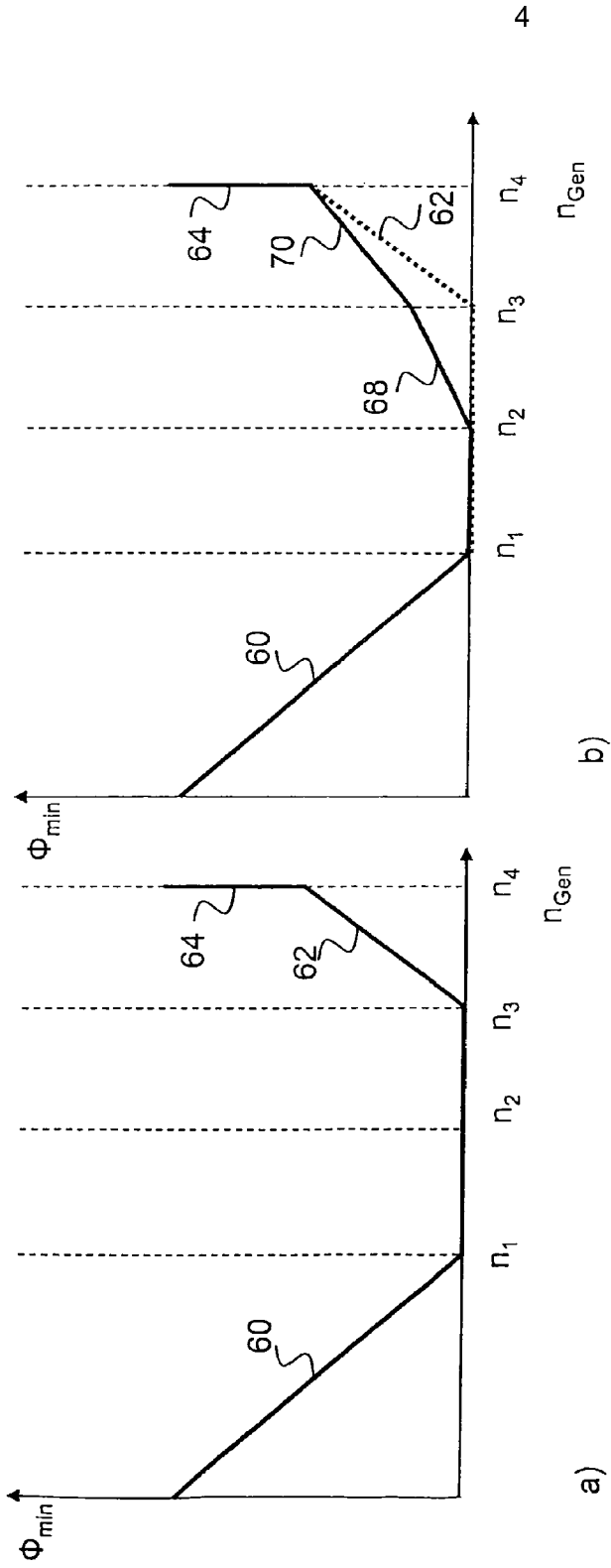


Fig. 4