

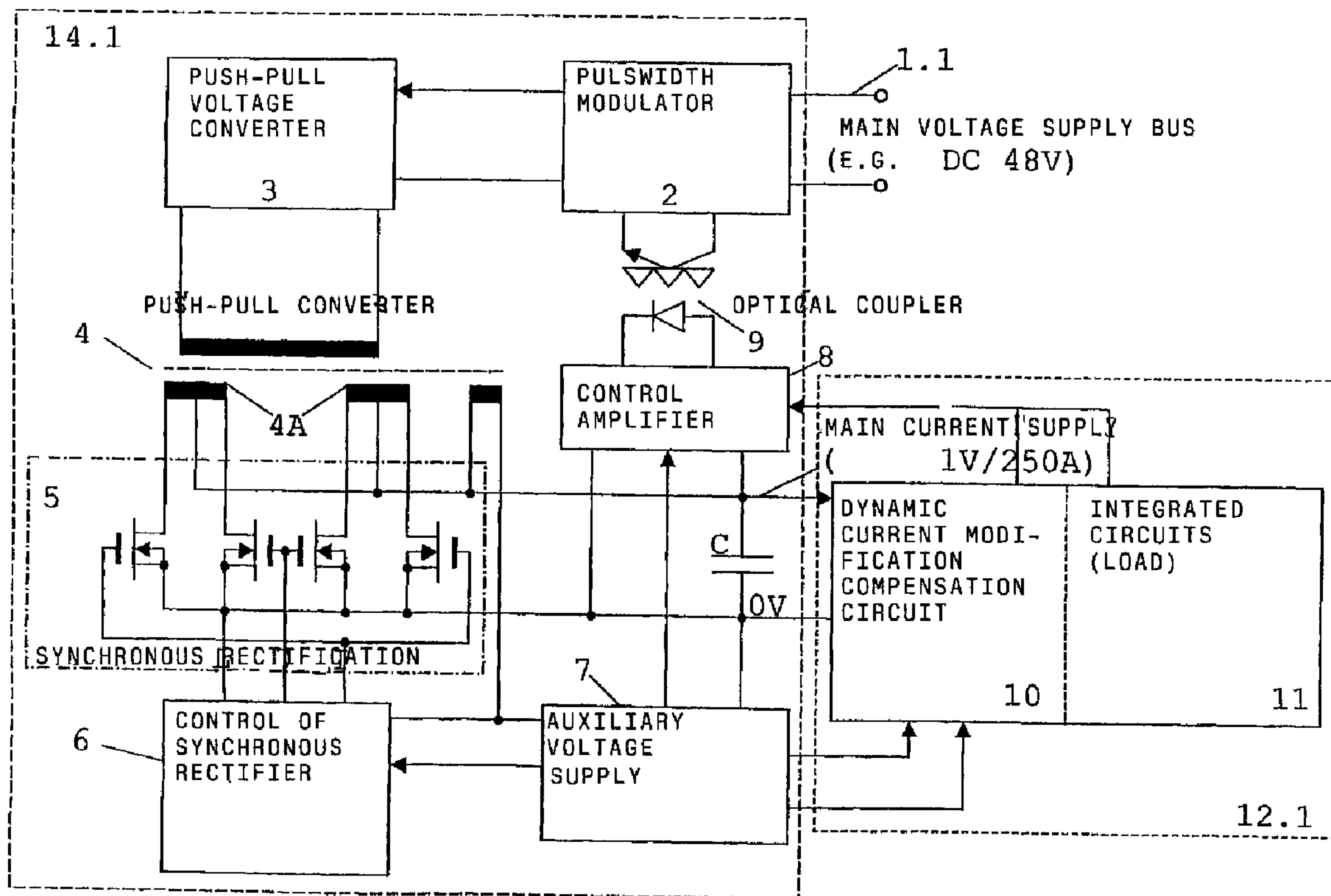


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 (72) Inventeur/Inventor:
 KAUFMANN, MICHAEL, DE
 (73) Propriétaire/Owner:
 MK ELEKTRONIK GMBH, DE
 (74) Agent: MARKS & CLERK

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 (54) Title: POWER SUPPLY FOR AN ELECTRONIC SYSTEM

DIAGRAM OF POWER SUPPLY



(57) Abrégé/Abstract:

According to prior art, a clock frequency increase for clocked high-frequency integrated circuits, in particular microprocessors, reaches a current physical limit of approximately 3 GHz, as dynamic current modifications cannot be sufficiently compensated. The

(57) **Abrégé(suite)/Abstract(continued):**

aim of the invention is to provide a power supply for electronic systems with a double-figure GHz range. To permit the rapid compensation of dynamic current modifications, the current compensation circuit (10) is placed in the vicinity of the integrated circuit (11) or is integrated into the latter. A control amplifier (8) influences a pulsewidth modulator (2) by means of an optical coupler (9). Said pulsewidth modulator control controls a normal mode voltage converter (3, 4) with synchronous rectification (5). A specific application area for the invention is the supply of future high-performance microprocessors, whose development has been delayed by the aforementioned power problem.

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US): MK-ELEKTRIK-GMBH [DE/DE]; Kirchdorfer
Str. 1, 87748 Fellheim (DE).

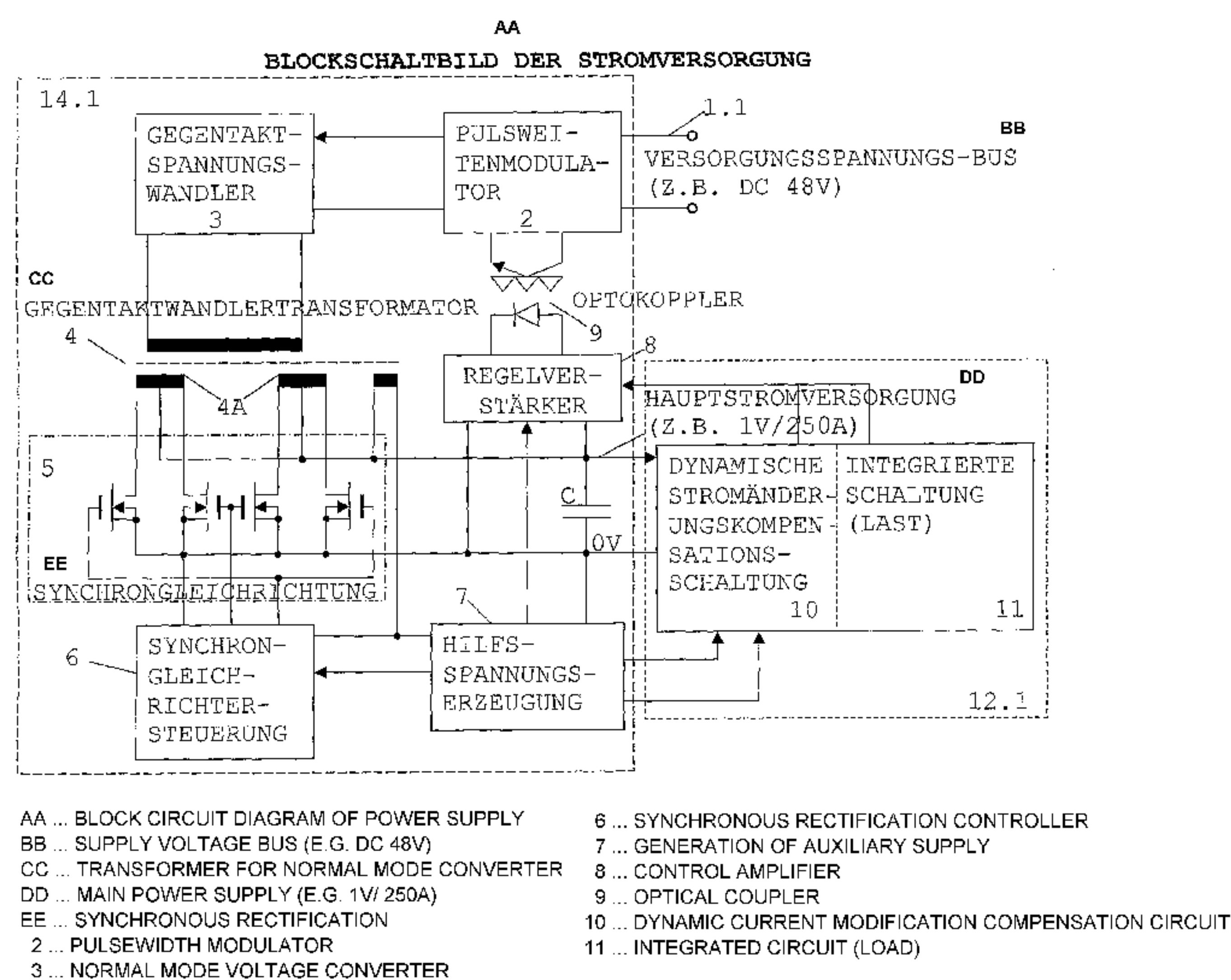
(72) Erfinder; und

(75) Erfinder/Anmelder (nur für US): KAUFMANN,
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(54) Title: POWER SUPPLY FOR AN ELECTRONIC SYSTEM

(54) Bezeichnung: ELEKTRONIKSTROMVERSORGUNG



(57) **Abstract:** According to prior art, a clock frequency increase for clocked high-frequency integrated circuits, in particular microprocessors, reaches a current physical limit of approximately 3 GHz, as dynamic current modifications cannot be sufficiently compensated. The aim of the invention is to provide a power supply for electronic systems with a double-figure GHz range. To permit the rapid compensation of dynamic current modifications, the current compensation circuit (10) is placed in the vicinity of the integrated circuit (11) or is integrated into the latter. A control amplifier (8) influences a pulsewidth modulator (2) by means of an optical coupler (9). Said pulsewidth modulator control controls a normal mode voltage converter (3, 4) with synchronous rectification (5). A specific application area for the invention is the supply of future high-performance microprocessors, whose development has been delayed by the aforementioned power problem.

(57) **Zusammenfassung:** Nach bisherigem Stand der Technik stößt eine Taktfrequenzerhöhung für hochfrequent getaktete Integrierte Schaltungen, insbesondere Mikroprozessoren, an physikalische Grenzen von derzeit ca. 3 GHz, da dynamische Stromänderungen nicht in ausreichender Weise ausgeglichen werden können. Die neue Elektronikstromversorgung soll einen zweistelligen GHz-Bereich eröffnen. Um eine schnelle Ausregelung dynamischer Stromänderungen zu ermöglichen, wird die Stromkompensation (10) in nächster Nähe zur Integrierten Schaltung (11) plziert oder darin

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- *hinsichtlich der Berechtigung des Anmelders, ein Patent zu beantragen und zu erhalten (Regel 4.17 Ziffer ii)*
- *Erfindererklärung (Regel 4.17 Ziffer iv)*

Zur Erklärung der Zweibuchstaben-Codes und der anderen Abkürzungen wird auf die Erklärungen ("Guidance Notes on Codes and Abbreviations") am Anfang jeder regulären Ausgabe der PCT-Gazette verwiesen.

selbst integriert. Ein Regelverstärker (8) nimmt über einen Optokoppler (9) Einfluß auf einen Pulsweitenmodulator (2) . Darüber wird eine Gegentaktspannungswandlung (3, 4) mit Synchrongleichrichtung (5) geregelt. Spezielles Anwendungsgebiet ist die Versorgung zukünftiger Hochleistungsmikroprozessoren, deren Entwicklung durch das aufgetretene Power-Problem verzögert wurde.

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Power Supply for an Electronic System

The invention refers to a power supply for electronic systems for electronic circuits with high operational frequency. In the recent decades the computing performance of computers doubled according to "Moore's Law" each time at an average of one and a half years. This increase of performance was reached by semiconductor structures which became smaller and smaller, subsequently increasing integration density and the continuous acceleration of the clock frequency which became possible through that. The effect for the power supply of these systems was a step-by-step reduction of the operating voltage while the operating current increased accordingly. In addition to the increase of the control accuracy necessary because of that together with the clock frequency the dynamic requirements of the power supply increased considerably.

In present high performance processors, operating at about 2 to 3 GHz clock frequency, the operating voltage may not exceed more than $\pm 5\%$ (about ± 0.05 to 0.075 V) when the dynamic load current modifications are about 350 A/ μ s so that a proper function of the processor is not impaired.

If the main feed lines have a length of only about 1.5 cm and a width of 1 cm and a conductor spacing of 1.5 mm (double-laminated circuit board) the result will be a conduction inductance of about 3 nH. A dynamic current modification of 350 A/ μ s thus induces at the main feed line already spikes of about ± 1 V, that means about $\pm 70\%$ of the operating voltage at $U_B = 1.5$ V.

In the present state of the art they try to solve these dynamic requirements with point-of-load-DC/DC-converters with high operating frequency - in actual variation carried out as polyphase step-down converter with synchronous rectification and digital phase control and adjustment - as well as a larger number of supporting capacitors distributed across the chip area, a high number of main feed contacts distributed across the entire processor chip minimising the main feed inductance.

In order to be able to replace highly capacitive supporting capacitors with a small number of small capacitors with lower ESR and smaller inductance also DRC circuits (dynamic load transient response circuit), e.g. by Ericsson or according US patent 6,472,855B2, are used.

Despite the application of such techniques the efforts to further accelerate the clock rate have reached a physical limit (called a "power problem" in professional papers). The CPU clock frequency of 15 GHz, still predicted in December

2003 for 2005, seems unachievable according to the present state of the art. Additional design measurements on chip level, like X architecture, the division into several power supply regions connected with outer supporting capacitors, and other measurements could only reach a clock frequency of about 4 GHz as superior limit frequency which could not even be exceeded by other structure reductions.

Neither the transistor cells limit frequencies of more than 70 GHz, achievable already with structural widths of 90 nm, nor the possible thermal carrying-off of heat of 1 kW/cm² (at $\Delta T \approx 5^\circ\text{C}$ between chip and steam temperature) with have reached their limits according to the present state of the art.

Causes of trouble for uncontrolled system crashes, when the presently possible clock rates are exceeded, are the operating voltage peaks (transients) proportional to the clock frequency and to the operating current which, despite a relatively high number of supporting capacitors bonded at the chip, considerably exceed or fall below starting with a certain clock frequency the still safe operating voltage region of $\pm 10\%$. The dynamic modifications of the operating current, caused by bit parity fluctuations (parity noise) depending on software and data flow, with the clock frequency which generate these current spikes at inductance and ESR of the supporting capacitors.

Arithmetic Example

With the operating data of a typical processor, 1.5 V operating voltage U_B at 40 A power consumption, 2 GHz clock frequency, 20 supporting capacitors size 1210 (3.2 x 2.4 x 2.5 mm):

40 A/20 \rightarrow 2A/capacitor \rightarrow with 1 % current noise with 0.25 ns pulse width a dynamic current modification of $\pm 0.02 \text{ A}/0.25 \text{ ns} \approx \pm 8 \times 10^7 \text{ A/s}$ at the supporting capacitor is the result.

With a middle capacitor spacing of 2.5 mm/2 + 0.25 mm from the chip the inductance formed with the chip can be assessed with the formula $L_c = \mu_0 \cdot A/l$:

$$L_c = \mu_0 \cdot 1.5 \text{ mm} \cdot 2.5 \text{ mm}/2.5 \text{ mm} \approx 1.9 \text{ nH}$$

Thus the voltage induced at this inductance by current noise is:

$$\pm 8 \cdot 10^7 \text{ A/s} \cdot 1.9 \text{ nH} \approx \pm 0.15 \text{ V}$$

This value corresponds with the operating voltage peaks of $\pm 10\%$ U_B just allowed for a fault free operation.

In addition to that the problem becomes even worse because with increasing integration density (of 130 nm → 90 nm → 45 nm structural width, the latter corresponding with the C-Mos gate length) and with increasing operating current the operating voltage has to be reduced from 2 V to 0.9 V, and the number of supporting capacitors can hardly be increased and their size and chip spacing cannot be reduced. This clarifies the barrier generally seen as "physical limit" for a further clock frequency rise.

It is an object of the invention to provide an electronic power supply which allows operation of integrated circuits with clearly higher operating frequencies than are typically possible currently.

The shifting of the dynamic operating voltage stabilization (by means of current modification compensation circuits) from the millimetre range of the circuit board into the micrometer range of the semiconductor chip level reduces the current line inductance to the load (power consumer circuits) by the same scale factor. When the tolerance width for the operating voltage transient is the same, according to the invention, the clock frequency may be increased theoretically by the reciprocal scale factor.

Simple current modification compensation circuits may here be realised, for example with a few transistors (Miller integrator) capacitively inverse-coupled by the operating voltage, which are connected in parallel to the CPU operating voltage at suited points in or at the semiconductor chip as shunt control. Depending on the application case with about 1 to 10 % shunt current (local share of operating current) all occurring dynamic current modifications can be almost completely adjusted to maximum of power and reduced to the main feed lines to the outer power supply to about 1 % of the one generated by the IC.

The invention has the advantage that sources of current noise on the main feed lines and at the supporting capacitors cannot induce any more spikes impairing the safe operation. This allows, besides an increase of the clock frequency by approximately factor 10, also a reduction of the number of supporting capacitors and feed voltage conduct contacts to the chip by about 90 %, so that the production costs can be lowered considerably and the reliability is improved clearly. The chip architecture may be simplified when the invention is

applied so that effort and time for design are reduced considerably.

Program-dependent operating current modifications of about 20 % to 110 % with maximum 3 % of the clock frequency have to be adjusted to maximum of power by the processor main power supply while keeping $U_B \pm 10$ %. In order to comply with these requirements even with clock frequencies of about 25 GHz it becomes necessary to place the main power supply in the shortest possible distance to the micro processor (that means directly above it), and to optimise this further compared with the state of the art. Such a power supply optimised in different sub-functions which makes the synergy effects of these improvements for increase of the efficiency with a considerable rise of the reliability and at the same time reduction of the production costs possible is described in the following embodiments.

An embodiment of the invention is to place the low voltage power supply above the chip carrier of the integrated circuit. The result is that power feed lines which are as short as possible to the integrated circuit make a shortened time for adjustment to maximum power of the supply voltage of the integrated circuit possible. Furthermore it is achieved by that that the previously required space for the power supply on the carrier board of the integrated circuit is no more necessary.

In another embodiment the integrated circuit and low voltage power supply are cooled by a common cooling block. The effect is that the effort for a separate cooling for the power supply is not necessary, and a common excess temperature safety for load and supply becomes possible. In addition to that the cooling block may serve, when designed as mechanic part of the low voltage power supply, also for the main feed line to the consumer.

In another embodiment the control of the low voltage power supply - with or without galvanic separation - is carried out primary before the transformation to the supply voltages of the integrated circuits. By means of that it is achieved that the control can be carried out at primary current reduced by the transformer translation ratio. This reduces the production costs and increases the efficiency of the power supply.

Furthermore it is achieved that previously necessary DC intermediate circuit converter modules now can be saved as the low voltage power supply with galvanic separation can be operated directly at the supply bus (e. g. 48 V).

Furthermore it is achieved that an increase of the supply voltage, hazardous for the integrated circuit, through failure

of a synchronous rectifier stage or its control cannot occur anymore according to the invention.

In another embodiment of the invention the leakage inductance of a push-pull converter is used as storage inductance for the low voltage power supply. By means of that according to the state of the art saving of additionally required storage inductance is achieved.

In a further embodiment the primary pulse width modulation frequency is many times the push-pull converter frequency. This achieves that the switch frequency for the synchronous rectifiers is 20 to 50 times below the state of the art, and therefore accordingly lower switch losses occur.

Another embodiment provides that the push-pull secondary windings, each comprising a double winding, are applied on the transformer outer limbs, and are connected in parallel on synchronous rectification. Thus, according to the invention, with the same current load the number of transistors required for synchronous rectification is now half compared with the previous state of the art.

In another embodiment by means of performance over-dimensioning the power supply may serve additionally as point-of-load-converter for peripheral circuits. The effect is that no space is required for the power supply of peripheral circuits.

According to an aspect of the invention, there is provided a power supply for an electronic system wherein dynamic current modification compensation circuits are placed in the direct vicinity of the points of origin of the current modifications, for example, accumulating registers, cache memories, data bus drivers, etc., or are integrated in the integrated circuit itself.

According to another aspect of the invention there is provided a power supply for an electronic system for high-frequency operated or clocked integrated circuits with compensation of dynamic operating current modifications directly at points of origin, dynamic current modification compensation circuits being placed in a direct vicinity of the points of origin of the current modifications or being integrated in an integrated circuit, so that sources of current noise on main feed lines and at supporting capacitors cannot induce any more voltage peaks.

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In one aspect, the invention provides a power supply arrangement connectable to a high-frequency operated or clocked integrated circuit, the arrangement comprising: a power supply for providing a main current supply for the integrated circuit in use; and a dynamic current modification compensation circuit for compensating for current modifications originating within the supplied integrated circuit, wherein the dynamic current modification compensation circuit is separated from the main power supply and located in close or closest proximity possible to sources of said current modifications originating within the integrated circuit to inhibit voltage peaks on feed lines of the integrated circuit.

In one aspect, the invention provides a high-frequency operated or clocked integrated circuit comprising feed lines for receiving a main current supply from a power supply arrangement, the integrated circuit including a dynamic current modification compensation circuit for compensating for current modifications in the integrated circuit and the main current supply, wherein the dynamic current modification compensation circuit is separated from the power supply and located in close proximity or closest proximity possible to sources of said current modifications originating within the integrated circuit to inhibit voltage peaks within feed lines of the integrated circuit.

According to an aspect of the present invention there is provided a power supply arrangement connectable to a high frequency operated or clocked integrated circuit, the power supply arrangement comprising:

a main power supply arranged completely external to the integrated circuit and arranged to provide a main current supply for the integrated circuit by way of feed lines external to the integrated circuit; and

a dynamic current modification compensation circuit for compensating for current modifications originating from internal feed lines of the integrated circuit, said dynamic current modification compensation circuit being

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arranged completely within the integrated circuit and adjacent to said current modifications to inhibit voltage peaks on said internal feed lines,

wherein the dynamic current modification compensation circuit is connected in parallel to a supply voltage of the integrated circuit and the dynamic current modification compensation circuit is designed to act as a shunt current control unit.

According to another aspect of the present invention there is provided a high-frequency operated or clocked integrated circuit comprising:

feed lines for receiving a main current supply from a main power supply; and

a dynamic current modification compensation circuit for compensating for current modifications originating from internal feed lines of the integrated circuit, said dynamic current modification compensation circuit being embedded completely within the integrated circuit and in close proximity to said current modifications to inhibit voltage peaks on said internal feed lines,

wherein the dynamic current modification compensation circuit is connected in parallel to a supply voltage of the integrated circuit and the dynamic current modification compensation circuit is designed to act as a shunt current control unit.

The drawing illustrates basic examples of the invention. In the drawings:

Fig. 1 a block diagram of the power supply for an electronic system with compensation of dynamic current modifications directly at the point of origin,

Fig. 2 a basic mechanic structure of the power supply for an electronic system and integrated circuit which has to be fed with common cooling.

Detailed Description of an Exemplary Embodiment

A power supply for an electronic system requires a main supply or a supply BUS connection (1.1 or 1.2). The pulse width modulation (2) determines the current consumption of the push-pull voltage converter (3). The push-pull voltage converter (3) forms a square wave voltage of the integrated average value of the pulse width modulation output voltage. By means of the push-pull converter (4) the push-pull output voltage is transformed into the desired main current supply voltage as well as the required auxiliary voltages. In the synchronous

rectifier (5) the transformed push-pull voltages for the main current supply are rectified and connected in parallel. The generation of auxiliary voltage (7) is supplied by another secondary winding on the push-pull voltage converter (4). At the same time this secondary winding serves for the control of the synchronous rectifier (6). The control amplifier (8) fed by the auxiliary voltage generator (7) compares the voltage of the main current supply with a built-in reference, and transmits the deviation via an optical coupler (9) to the control of the pulse width modulator (2). The auxiliary voltage supply (7) feeds, beside the main current supply, also the control electronic system of the dynamic current modification compensation circuit (10). By means of that modifications of the voltage at the load (11) are almost completely adjusted to maximum of power.

Temperature safety functions can be realised via a control signal generated by the dynamic current modification compensation circuit (10) or the integrated circuit (11). When a value to be selected below the permissible chip temperature (for example -30K compared with maximal permissible chip temperature) is reached here the control amplifier (8) is activated to reduce main current supply and auxiliary voltages in a controlled manner. With a redundant design the control amplifier (8) may be able to reduce on its own the main current supply and auxiliary voltages when a given temperature is exceeded.

In the mechanic construction a cooling block (13) of electrically and thermally conductive material (for example copper) is applied on the chip carrier (12.2) which has to be through hole plated to the top. This cooling block is segmented in order to make a positive and negative current flow possible, connections for auxiliary voltages are led through the cooling block. The transformer secondary windings for the main current supply are formed by conductive form parts embracing the transformer outer limbs, and connected with segments of the cooling block carrying plus and minus, and serve as carrier of the MOS-FETs of the synchronous rectifier as well as for their heat elimination. Capacitors (C) bridge the segments carrying plus and minus and act as integration capacitors for the power supply (14.1) and as supporting capacitors for the load (11) as well as the dynamic current compensation circuit (10).

Above load (11) and dynamic current modification compensation circuit (10) in the cooling block evaporation chambers for the cooling liquid are arranged which is fed by the interior pipe (15.1) of the coaxial line (15). Cooling liquid in the vapour state may be removed via the outer pipe (15.2).

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A power supply arrangement connectable to a high frequency operated or clocked integrated circuit, the power supply arrangement comprising:

a main power supply arranged completely external to the integrated circuit and arranged to provide a main current supply for the integrated circuit by way of feed lines external to the integrated circuit; and

a dynamic current modification compensation circuit for compensating for current modifications originating from internal feed lines of the integrated circuit, said dynamic current modification compensation circuit being arranged completely within the integrated circuit and adjacent to said current modifications to inhibit voltage peaks on said internal feed lines,

wherein the dynamic current modification compensation circuit is connected in parallel to a supply voltage of the integrated circuit and the dynamic current modification compensation circuit is designed to act as a shunt current control unit.

2. The power supply arrangement according to claim 1, wherein the dynamic current modification compensation circuit is measured in micrometers.

3. The power supply arrangement according to claim 1 or 2, wherein the integrated circuit and the power supply both are cooled by a common cooling block.

4. The power supply arrangement according to claim 1,

2 or 3, wherein control of the power supply is carried out before transformation, to supply voltages of the integrated circuit.

5. The power supply arrangement according to claim 4, wherein the integrated circuit may or may not comprise galvanic separation.

6. The power supply arrangement according to any one of claims 1 to 5, wherein the main current supply comprises a push-pull converter and uses the leakage inductance of said push-pull converter as storage inductance for the power supply.

7. The power supply arrangement according to any one of claims 1 to 6, wherein the main power supply comprises a primary pulsewidth modulator with a modulation frequency which is a multiple of the push-pull converter frequency.

8. The power supply arrangement according to claim 5 or 7, wherein the push-pull converter has secondary windings, each comprising a double winding, which are located on transformer outer limbs of the push-pull converter and are connected in parallel on synchronous rectification.

9. The power supply arrangement according to any one of claims 1 to 8, wherein the power supply includes additional reserve power that can additionally serve as point-of-load-converter for peripheral circuits.

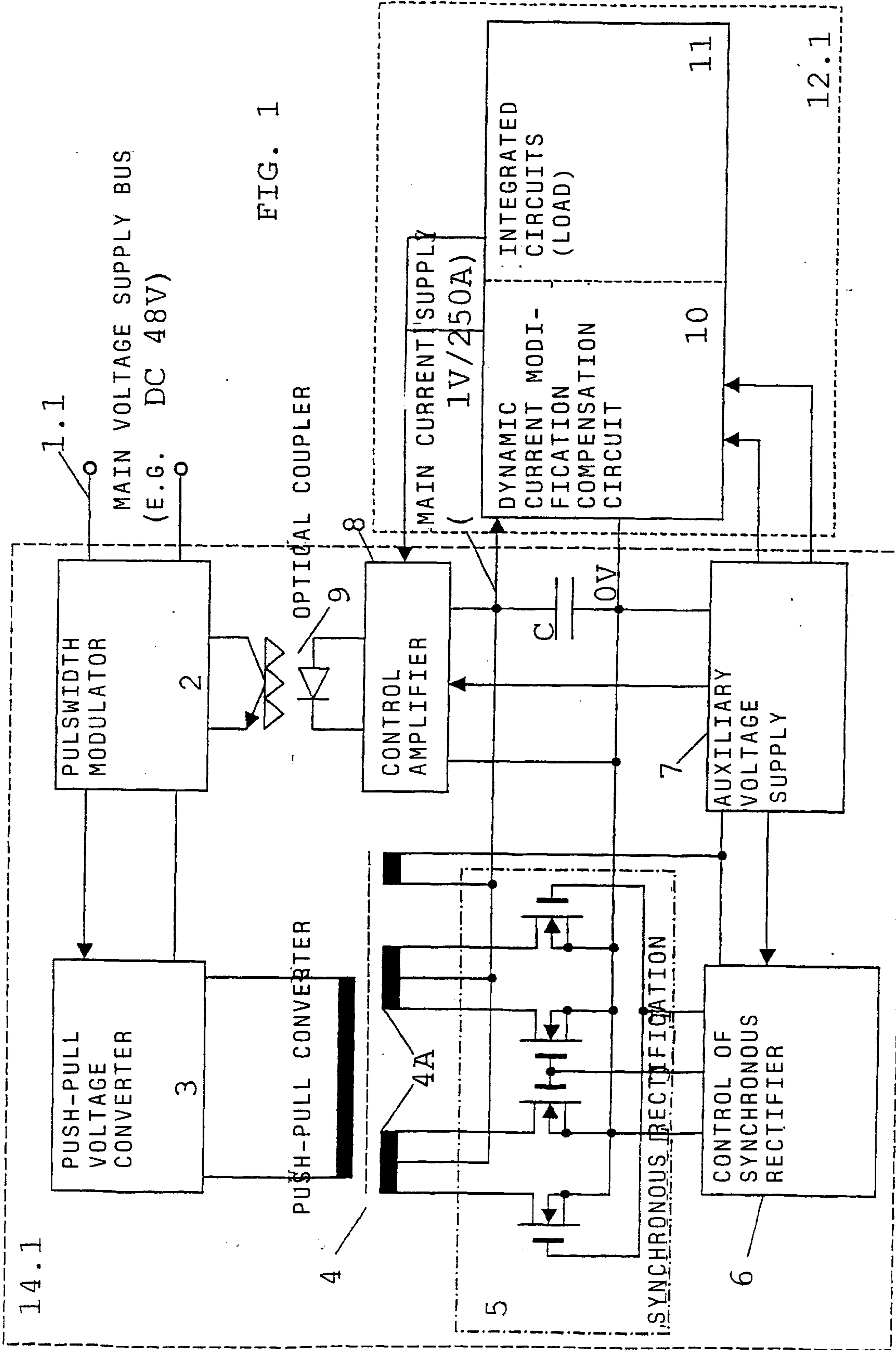
10. A high-frequency operated or clocked integrated circuit comprising:

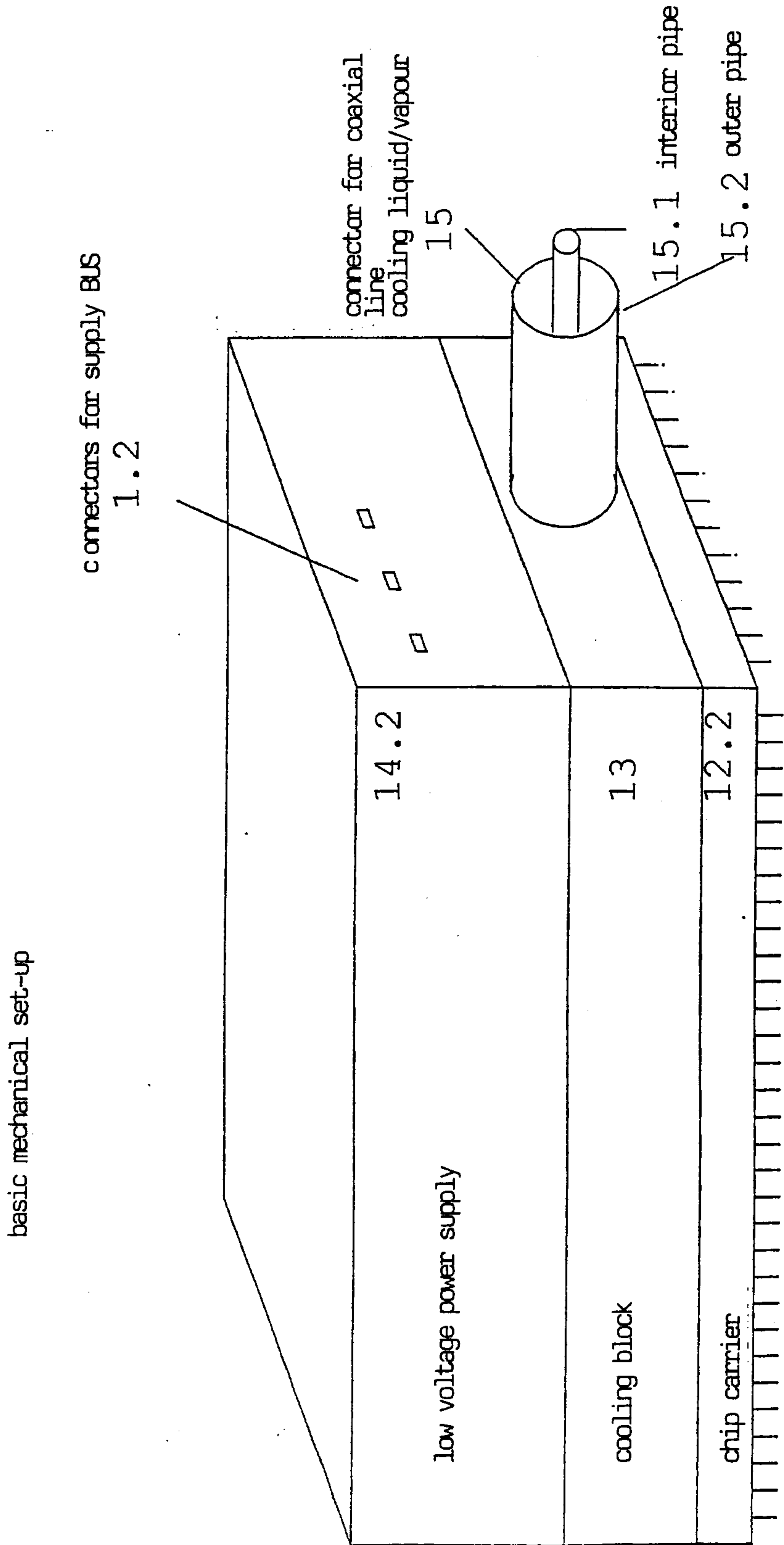
feed lines for receiving a main current supply from a main power supply; and

a dynamic current modification compensation circuit for compensating for current modifications originating from internal feed lines of the integrated circuit, said dynamic current modification compensation circuit being embedded completely within the integrated circuit and in close proximity to said current modifications to inhibit voltage peaks on said internal feed lines,

wherein the dynamic current modification compensation circuit is connected in parallel to a supply voltage of the integrated circuit and the dynamic current modification compensation circuit is designed to act as a shunt current control unit.

DIAGRAM OF POWER SUPPLY





for integrated circuit
(e.g. for micro processors)

FIG. 2

DIAGRAM OF POWER SUPPLY

