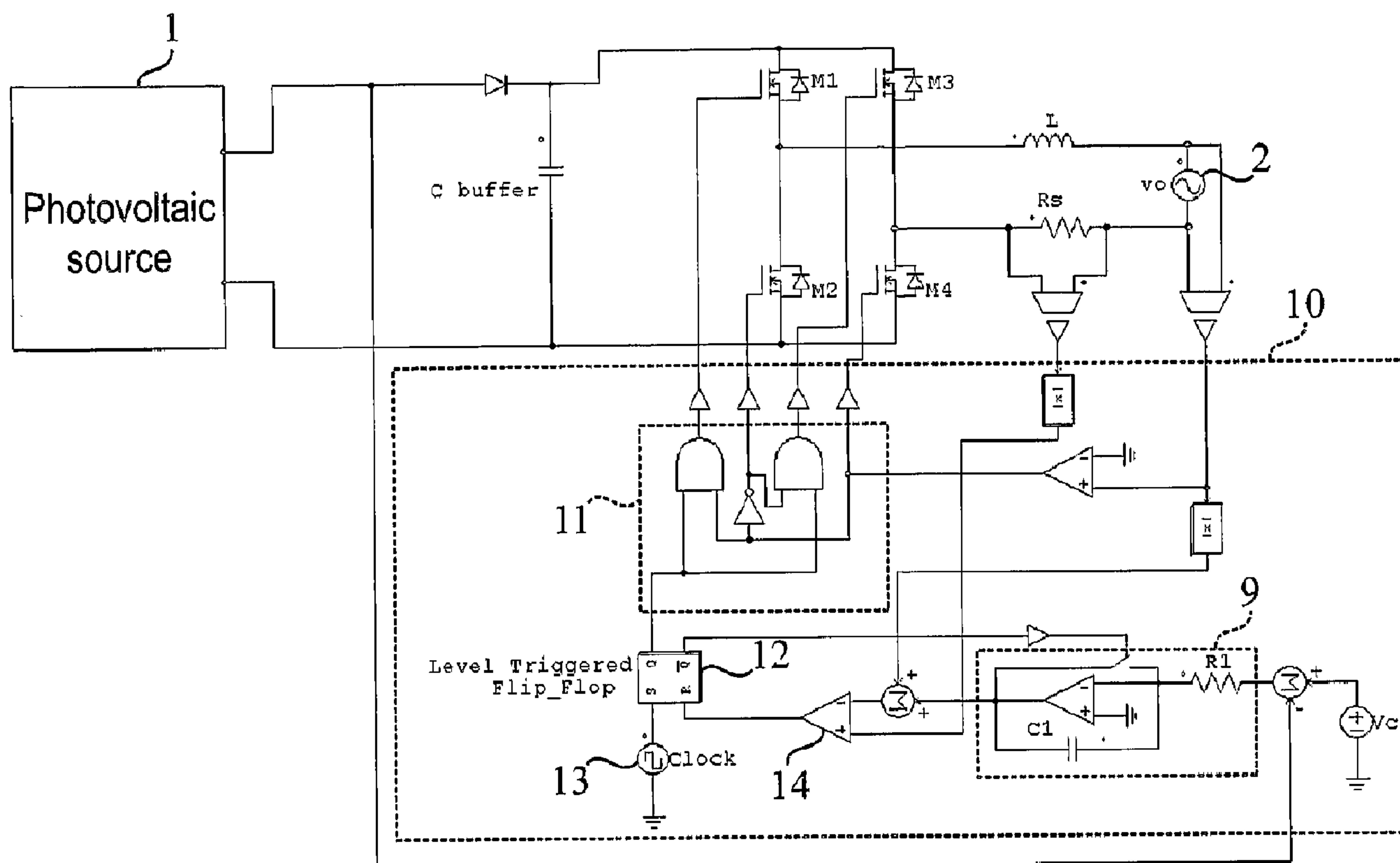




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(54) Titre : INVERSEUR A ETAGE UNIQUE ET PROCEDE DE CONTROLE CONNEXE POUR CONVERTISSEURS DE PUISSANCE A PARTIR DE SOURCES D'ENERGIE, EN PARTICULIER PHOTOVOLTAIQUES  
(54) Title: SINGLE STAGE INVERTER DEVICE, AND RELATED CONTROLLING METHOD, FOR CONVERTERS OF POWER FROM ENERGY SOURCES, IN PARTICULAR PHOTOVOLTAIC SOURCES



(57) Abrégé/Abstract:

The present invention concerns a single stage inverter device for power converters, comprising switching means (M1-M4) capable to periodically connect an energy source (1), in particular a photovoltaic one, to an electric network or grid (2), the switching means (M1-M4) being controlled by controlling electronic means (10, 20) operating according to a single switching cycle control of the



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

switching means (M1-M4), the operative and circuit device parameters being such to fulfill a series of constraints simultaneously optimising both the maximum power point tracking or MPPT (Maximum Power Point Tracking) and the output power factor or PF-out (Power Factor-output) for one or more operation conditions. The present invention further concerns the related method of controlling and the related method of scaling such device.

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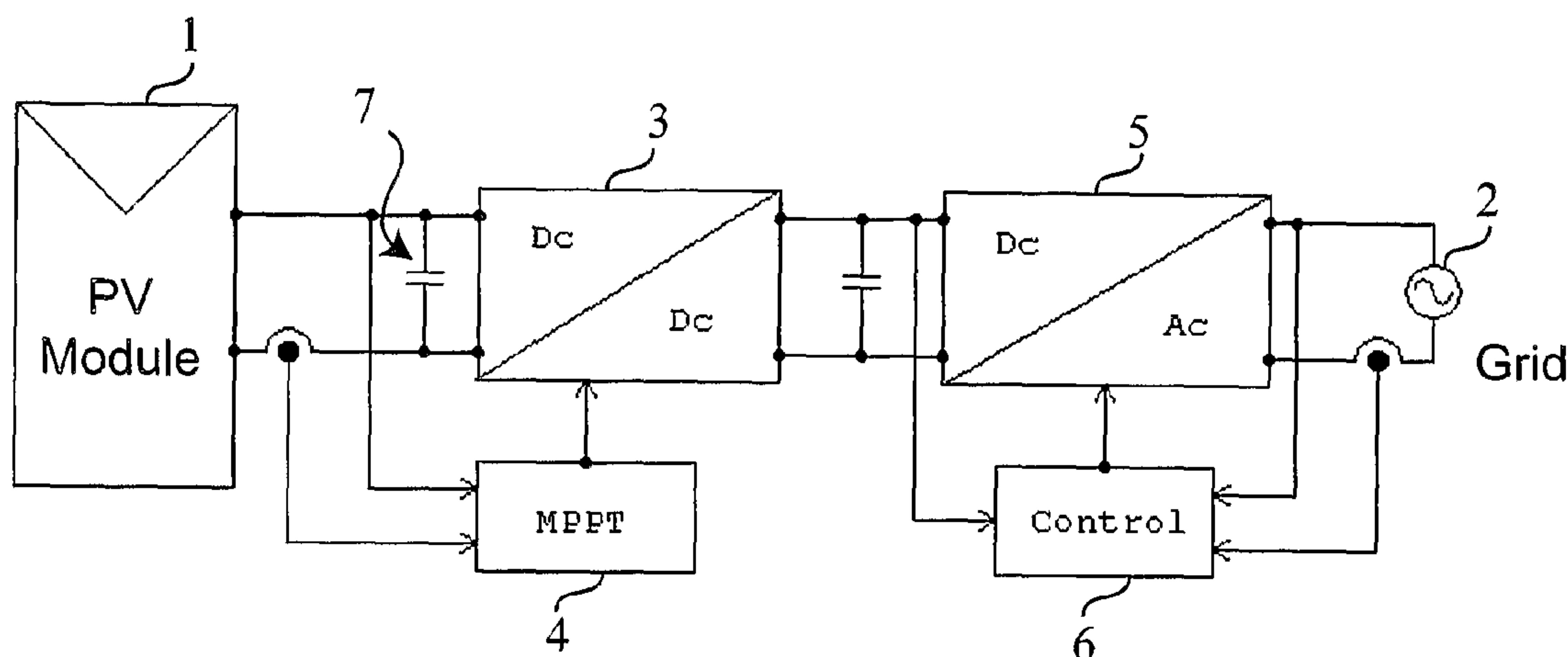
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(54) Title: SINGLE STAGE INVERTER DEVICE, AND RELATED CONTROLLING METHOD, FOR CONVERTERS OF POWER FROM ENERGY SOURCES, IN PARTICULAR PHOTOVOLTAIC SOURCES



(57) Abstract: The present invention concerns a single stage inverter device for power converters, comprising switching means (M1-M4) capable to periodically connect an energy source (1), in particular a photovoltaic one, to an electric network or grid (2), the switching means (M1-M4) being controlled by controlling electronic means (10, 20) operating according to a single switching cycle control of the switching means (M1-M4), the operative and circuit device parameters being such to fulfill a series of constraints simultaneously optimising both the maximum power point tracking or MPPT (Maximum Power Point Tracking) and the output power factor or PF-out (Power Factor-output) for one or more operation conditions. The present invention further concerns the related method of controlling and the related method of scaling such device.

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SINGLE STAGE INVERTER DEVICE, AND RELATED CONTROLLING METHOD, FOR CONVERTERS OF POWER FROM ENERGY SOURCES, IN PARTICULAR PHOTOVOLTAIC SOURCES

5           The present invention concerns a single stage inverter device for a power electronic converter, with alternate current output and direct current input (dc-ac), for energy sources, in particular renewable energy sources, preferably photovoltaic sources, based on the so called switching one-cycle control or OCC technique, with maximum power point tracking or  
10   MPPT that is static or possibly dynamically adaptive through Perturb&Observe or P&O technique, the device being simple, reliable, efficient, precise, and inexpensive, simultaneously optimising both the MPPT control and the output Power Factor or PF-out of the dc-ac converter, so as to possibly also achieve the real maximum power point  
15   tracking of the photovoltaic field through dynamic adaptation to the operation instant conditions of the photovoltaic field.

          The present invention further concerns the related method of scaling the characteristic parameters of such inverter device and the related controlling method.

20           In the following description specific reference will be made to the application of single-phase power dc-ac converters for energy photovoltaic sources known as so-called "grid-connected" systems (connected to an alternate current electric energy distribution network), but it should be understood that the inverter device (and the related controlling method)  
25   according to the invention may be applied to both single-phase and multi-phase converters for any energy source, in particular renewable, such as fuel cells, wind turbines, and other sources having a variable maximum power point, or more generally a maximum energy convenience point maximum energy convenience point, at the input, and a constrained PF-out at the output. More in general, the inverter device according to the  
30   invention may be applied to converters for any energy source that is characterised by the existence of particular specific operation conditions which are deemed preferential, in relation to produced energy, energy efficiency, component stress degree, life, or any other evaluation factor  
35   may be defined for a specific source, and which conditions are variable, due to climatic or physical factors or factors of any nature, which are either controllable or uncontrollable, either predictable or unpredictable, and identifiable through a particular point of one of the source output electrical

characteristic curves such as power-voltage, power-current, voltage-current, current-voltage, efficiency-voltage, efficiency-current or other ones similar thereto.

5 It is known that electronic power converters used in photovoltaic systems called "grid-connected" achieve the dual function of extracting the maximum power from the photovoltaic field (MPPT) and delivering the extracted power to the alternate current or AC network with high output Power Factor (PF-out), wherein the current is in phase with the voltage and presents a low harmonic distortion.

10 The market presently offers several photovoltaic inverters, generally based on a double stage architecture, of the type shown in Figure 1 for a single-phase application, interposed between the photovoltaic source 1 and the ac electric energy distribution grid 2. Such architecture presents as main advantage some ease of design and  
15 implementation thanks to the separation of the two functionalities of MPPT and dc-ac conversion with PF-out control: the first one is achieved by the dc-dc converter 3, controlled by the maximum power point tracking MPPT module 4 connected to the output of the source 1, while the functionality of dc-ac conversion is achieved through the dc-ac converter 5, controlled by  
20 the module 6 connected to the input of the grid 2.

Through a careful design of the controller of each stage, it is possible to attain satisfactory performance in terms of both efficiency of energy extraction from the photovoltaic field 1 and electric efficiency of conversion from the photovoltaic field 1 to the grid 2.

25 However, such system presents some drawbacks and limitations, such as: the high costs of the components of the two power stages; the performance decay at low levels of current; the basically slow dynamics due to the passage of energy through the dc bus sustained by a high-capacity bulk capacitor 7; the need of stabilising the bulk voltage without  
30 suppressing the grid second harmonic ripple.

Since the cost of a photovoltaic system is made up by about 50% by the cost of the photovoltaic modules and by 30-40% by the photovoltaic inverter, reducing the cost of the latter may be surely an interesting incentive to a wider diffusion of the use of renewable sources for  
35 producing electric energy, thus meeting a diffused social, economic, and environmental need.

Consequently, in the last years some devices have been

developed attempting to solve the problem of the costs of a photovoltaic inverter. Such solutions are based on:

- 5       - the use of single stage inverters, wherein the functionalities of MPPT, dc-ac inversion, and PF-out control are integrated in a single power circuit;
- the development of integrated control techniques allowing to achieve the combined function of MPPT, dc-ac inversion, and PF-out control; and
- 10       - the implementation of control circuits integrated on microchip, developed and optimised for ensuring the achievement of the functionalities necessary to the single stage photovoltaic inverter in a robust and adaptive way with respect to the characteristics of the source photovoltaic field.

15       In particular, Y. Chen and K.Ma. Smedley, in "*A cost-effective single-stage inverter with maximum power point tracking*", IEEE Transactions on Power Electronics, Vol. 19, No. 5, September 2004, pp. 1289-1294, have recently proposed the application of the OCC control, as shown in Figure 2, to a single stage inverter for photovoltaic use, wherein a dc-ac converter, connected at its input to the photovoltaic source 1 and  
20       at its output to the grid 2, comprises four semiconductor power switches M1-M4 (preferably implemented through respective MOSFETs or IGBTs). The single stage inverter is controlled by a driving unit 8, that operates on the basis of values of certain electric quantities at input and output of the same converter, through the One-Cycle Control technique, for controlling  
25       the voltage of a converter over a single switching cycle. More in detail, as also disclosed by K.M. Smedley, S. Cuk, "*One-cycle control of switching converters*", Power Electronics, IEEE Transactions on Volume 10, Issue 6, November 1995 pp. 625 - 633, the OCC technique is a non linear control technique that offers significant advantages in terms of line noise rejection and response speed, that is based on the integration function of  
30       a suitable variable (voltage or current), with switching waveform, in order to impose its average value equal to a value indicated by a control reference signal (in particular a control voltage  $V_c$ ).

35       However, the scaling of the OCC controller 19 of Figure 2, intended for a photovoltaic MPPT application, requires an adequate design/circuit approach and an accurate setting of the circuit parameters, in order to be able to really achieve both the MPPT control and the PF-out

optimisation with performance comparable to that of a present good performance double stage system. In the system of Figure 2, power passes from the photovoltaic field 1 to the grid 2 through the inverter, that operates as a so called buck converter (i.e. a dc-dc converter that provides for an output average voltage less than the input dc voltage by varying the duty cycle of a switch connecting the input to the output, i.e. the ratio between the time during which the switch is closed and the period of the periodic signal controlling the switch) in each half cycle of the frequency of the line 2 thanks to the control circuit 8.

By observing Figure 2, the inner pulse width modulation PWM loop is characterised by a high speed and it determines, cycle by cycle, the duty-cycle value necessary for obtaining a quasi-sinusoidal output current following the waveform of the line ac voltage  $v_o(t)$ . The outer loop, instead, is intended for the MPPT function and it adjusts the output power according to the maximum power that may be extracted from the photovoltaic field 1.

In the following of the present description and in the claims, the following correspondences between symbols and electric quantities will be used:

- $v_g(t)$  indicates the instant voltage generated by the photovoltaic field 1;
- $v_m(t)$  indicates a voltage instant value defined by the following equation

$$v_m(t) = \left( \frac{V_c - K_g \cdot v_g(t)}{R_l C_l} \right) \cdot T_s$$

where  $K_g$  is a constant,  $T_s$  is the switching period of the power stage, i.e. of the inverter switches M1-M4, and the other quantities are immediately comprehensible on the basis of Figure 2;

- $v_o(t)$  indicates the instant value of the voltage of the grid 2;
- $i_o(t)$  indicates the instant value of the inverter output current;
- $d(t)$  indicates the instant value of the inverter duty cycle;
- $v_g$ ,  $v_m$ ,  $v_o$ ,  $i_o$ , and  $d$  indicate the instant average values, i.e. the average values calculated over a switching period  $T_s$ , of the respective instant variables  $v_g(t)$ ,  $v_m(t)$ ,  $v_o(t)$ ,  $i_o(t)$ , and  $d(t)$ ;
- $V_g$  and  $V_m$  indicate the average values of the corresponding instant variables  $v_g(t)$  and  $v_m(t)$ , calculated over a period  $T_{grid}$  of the voltage  $v_o(t)$  of the grid 2; and

5

- $V_o$  and  $I_o$  indicate the effective values of the corresponding instant variables  $v_o(t)$  and  $i_o(t)$ , calculated over a period  $T_{grid}$  of the voltage  $v_o(t)$  of the grid 2.

5 Still making reference to Figure 2, as disclosed by Chen and Smedley, the OCC control ensures a high PF-out if the output current  $i_o(t)$  is proportional to the grid voltage  $v_o(t)$ , that is if:

$$i_o = (K_1 - K_2) \cdot v_o \quad [1]$$

where  $K_1$  and  $K_2$  are positive constants, the values of which determine the operation power levels of the inverter.

10 By multiplying equation [1] by the sensing resistance  $R_s$  and taking account of the conversion ratio of the buck converter, equal to

$$d = v_o / V_g$$

where  $d$  is the duty cycle and  $V_g$  is the average value of the dc voltage of the photovoltaic field 1 over a period  $T_{grid}$  of the voltage  $v_o(t)$  of the grid 2, equation [1] becomes:

$$R_s \cdot i_o = R_s \cdot K_1 \cdot v_o - R_s \cdot K_2 \cdot v_o = R_s \cdot K_1 \cdot v_o - R_s \cdot K_2 \cdot v_g \cdot d = K \cdot v_o - v_m \cdot d \quad [2]$$

where

$$K = R_s \cdot K_1 \quad \text{and}$$

$$v_m = R_s \cdot K_2 \cdot V_g \quad [3]$$

20 Consequently:

$$K \cdot v_o - R_s \cdot i_o(t) = v_m \cdot d \quad [4]$$

Equation [4] constitutes the basic relation for achieving the OCC control through the inner loop of Figure 2 .

25 The average output power  $P_o$  may be derived from equations [2][3] and [4]:

$$P_o = V_o \cdot I_o = V_o \cdot \left( \frac{K - \frac{V_m}{V_g}}{R_s} \right) \cdot V_o = \frac{V_o^2}{R_s} \cdot \left( K - \frac{V_m}{V_g} \right) \quad [5]$$

where  $V_o$  and  $I_o$  are the effective values of the output voltage and current,  $v_o(t)$  and  $i_o(t)$ , respectively. From Figure 2 and equation [3] it follows:

$$v_m = \left( \frac{V_c - K_g \cdot v_g}{R_1 C_1} \right) \cdot T_s \quad [6]$$

6

where  $K_g$  is a constant,  $R_1 \cdot C_1$  is the time constant  $\tau$  of the integrator circuit 9, and  $V_c$  is the control voltage.

Hence, the output power  $P_o$  is equal to:

$$P_o = \frac{V_o^2}{R_s} \left( K + \frac{K_g T_s}{R_1 C_1} - \frac{V_c T_s}{V_g R_1 C_1} \right) \quad [7]$$

5 Equation [7] gives the inverter output power  $P_o$  as a function of parameters  $K$ ,  $K_g$ ,  $V_c$ ,  $R_1$ ,  $C_1$ ,  $R_s$  and  $T_s$ . In particular, it indicates that it is necessary to adequately choose the aforesaid parameters in order to maximise the inverter output power  $P_o$ , i.e. the output power of the photovoltaic field 1.

10 For a stable operation of the OCC controller 19, Chen and Smedley have indicated the following conditions:

$$R_1 C_1 < T_s \quad [13]$$

$$V_c \geq K_g V_g + \frac{(2V_{o,max} - V_g) R_s R_1 C_1}{2L} \quad [14]$$

15 where  $V_c$  is the control voltage and  $V_{o,max}$  is the maximum value assumed by the output voltage  $v_o(t)$ . Therefore, the parameters characterising the OCC controller 19 of the system of Figure 2, determining its performance in photovoltaic applications, are the operative parameters  $K_g$ ,  $V_c$ , and  $K$ , and the circuit parameters  $R_1$ ,  $C_1$ ,  $R_s$ .

20 However, the converter proposed by Chen and Smedley, illustrated with reference to Figure 2, suffers from some drawbacks, due to the fact that the above constraints [13] and [14] do not ensure the real operation of the photovoltaic single stage inverter with maximum power point tracking (MPPT) and high PF-out in any operation condition, such as for instance in variable sunlight conditions.

25 In fact, in order to obtain a robust PF-out control it is necessary that, at any sun irradiance level  $S$  within the operation range  $[S_{min}, S_{max}]$  that is intended to ensure, the OCC controller 19 is capable to properly modulate the output current  $i_o(t)$  according to equation [4] and the output power  $P_o$  according to equation [5]. The average power  $P_o$  is modulated by the term  $(K - V_m/V_g)$  depending on the irradiance level  $S$  through the term  $V_m/V_g$ . Such ratio appears in equation [5] and hence the oscillations of the voltage of the photovoltaic field 1 translate into a perturbation of the term  $v_m(t)/v_g(t)$  that strongly affects the waveform of the output current  $i_o(t)$ .

30

In other words, Chen and Smedley have proposed design equations allowing infinite solutions (though corresponding to levels of efficiency of extraction of power from the photovoltaic field lower than the maximum one), but they have not been capable to give explicit and defined guidelines for setting the aforementioned parameters, nor systematic treatment of the problem and solution strategies are available in the technical-scientific literature. In fact, Chen and Smedley have presented only one example of solution based on the trial-and-error approach, that is of poor both technical-scientific and application interest, since it is the result of a non systematic approach and it does not give results ensuring good performance.

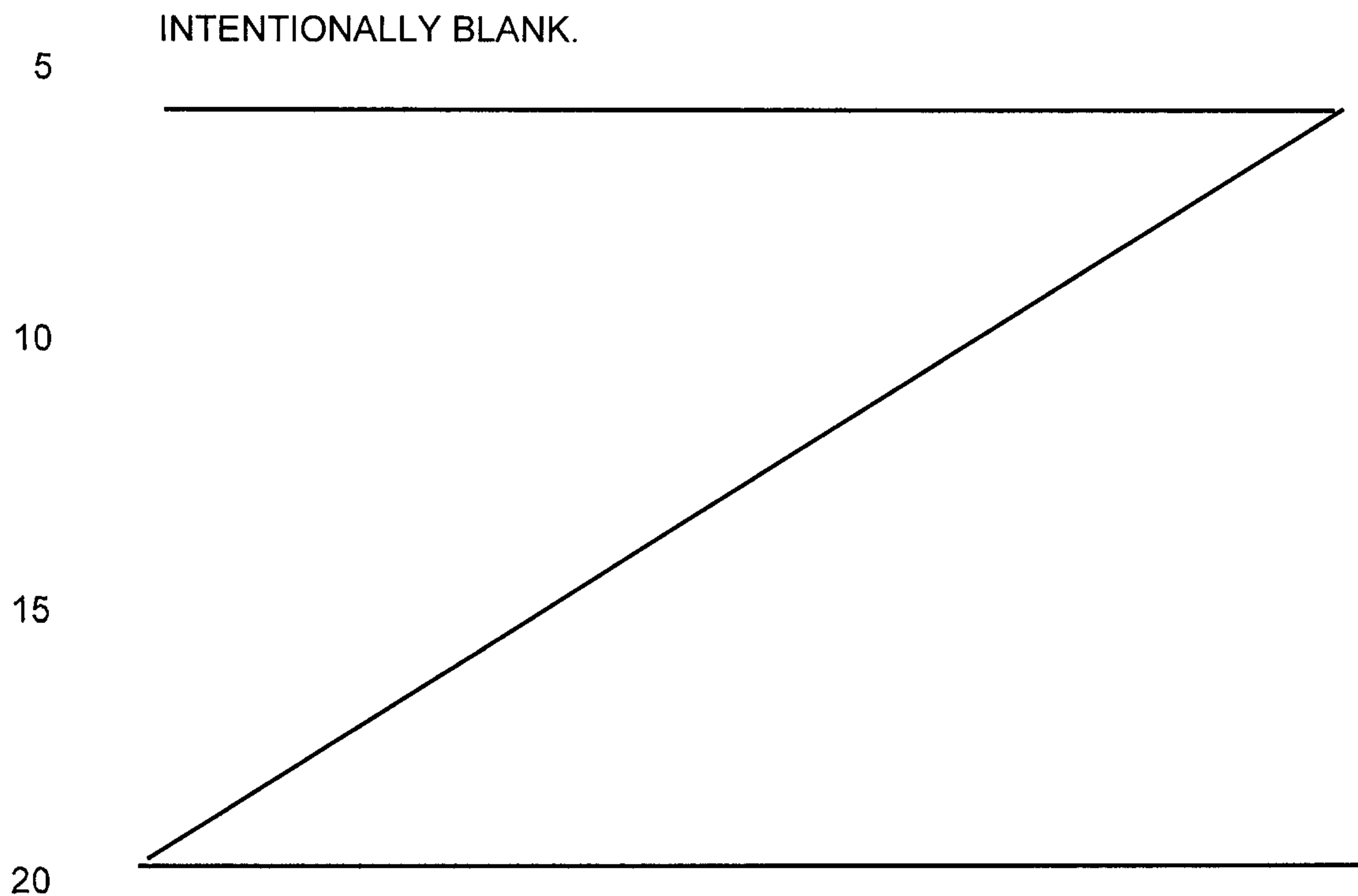
Therefore, the OCC technique applied to the nowadays available photovoltaic single stage inverter does not include in a reliable and efficient way the MPPT functionality simultaneously also optimising the PF-out, and it does not include a method for optimally determining or setting the parameters. In fact, the locus of the operation points of the OCC single stage inverter is identified by a static curve in the p-v (power-voltage) plane that does not intersect the p-v curve of the photovoltaic field in points corresponding to the maximum power points related to the various sunlight levels, except for a particular and unpredictable sunlight value.

It is therefore an object of the present invention to provide an OCC single stage inverter, capable to simultaneously optimise both the MPPT control and the output PF-out of a dc-ac converter connected between an energy source, in particular photovoltaic, and an electric network, the set of values of the parameters of which is identified in a fixed way, allowing to achieve the static curve, more preferably a set of static curves, of the inverter operation points that approaches as much as possible the locus of the maximum power MPP points of the source, for instance of the photovoltaic field, described according to the variation of the operation conditions, such as sunlight, temperature, and degradation of the efficiency of the photovoltaic field panels.

It is still an object of the present invention to provide an OCC single stage inverter the controller of which has a set of values of the parameters identified in a dynamically variable way when the operation conditions of the energy source vary.

It is a further object of the present invention to provide such a

photovoltaic inverter that is simple, reliable, efficient, precise, and inexpensive.



The present invention will now be described, by way of illustration and not by way of limitation, according to its preferred embodiments, by particularly referring to the Figures of the enclosed drawings, in which:

Figure 1 schematically shows a double stage inverter device of the prior art;

Figure 2 schematically shows a single stage inverter device of the prior art;

Figure 3 shows a preferred embodiment of the device according to the invention, having a first scaling of parameters;

Figure 4 shows the output power-voltage characteristic curves of the device of Figure 3;

Figure 5 shows the output currents from the device of Figure 3 in two respective operation conditions;

Figure 6 shows the output power-voltage characteristic curves of the device of Figure 3, having a second scaling of parameters;

Figure 7 shows the output currents from the device having the characteristic curves of Figure 6 in two respective operation conditions;

Figure 8 shows the output power-voltage characteristic curves of the device of Figure 3, having a third scaling of parameters;

Figure 9 shows the output currents from the device of Figure 3 having the third scaling of parameters in two respective operation  
5 conditions;

Figure 10 shows first graphs of the dynamic performance of the device of Figure 3 having the third scaling of the parameters in variable operation conditions;

Figure 11 shows a second graph of the dynamic performance of  
10 the device of Figure 3 having the third scaling of the parameters in variable operation conditions;

Figure 12 shows graphs of the performance of a first device not according to the invention;

Figure 13 shows graphs of the performance of a second device  
15 not according to the invention;

Figure 14 shows third graphs of signals internal to the device of Figure 3 having the third scaling of the parameters compared with similar signals internal to a third device not according to the invention;

Figure 15 shows a graph of the performance of the third device not  
20 according to the invention;

Figure 16 shows a graph of the performance of a fourth device not according to the invention;

Figure 17 shows graphs of the performance of the fourth device  
25 not according to the invention;

Figure 18 shows a second embodiment of the device according to  
the invention;

Figure 19 shows the output power-voltage characteristic curves of the device of Figure 18;

Figure 20 shows a graph of the performance of the device of  
30 Figure 18;

Figure 21 shows a graph of signals internal to the device of Figure 18;

Figure 22 shows graphs of the performance of the device of Figure 18 in variable operation conditions;

Figure 23 shows a particular of the internal signals and the output  
35 current of the device of Figure 18; and

Figure 24 shows further graphs of the performance of the device

of Figure 18 in variable operation conditions.

In the Figures, alike elements are indicated by same reference numbers.

5 The inventors have developed a new method for setting the optimal parameters of the control circuit of a photovoltaic single stage inverter, based on the one-cycle control technique, (i.e. the operative parameters  $K_g$ ,  $V_c$ , and  $K$ , and the circuit parameters  $R_1$ ,  $C_1$ ,  $R_s$ ), that allows to delimit the region of the inverter operation the points of which are located within a fixed distance from the maximum power point MPP of a photovoltaic field of given characteristics.

10 The first step of the optimisation method consists in just limiting the search space of the set of parameter values, represented by equations expressing constraints to meet, arriving to define a Region of Acceptability (RA) within the Space of Parameters (SP). In particular, the inventors have developed some new equations representing a constraint on the inverter PF-out that is valid over the whole range of power coming from the photovoltaic field that the inverter has to sustain.

15 Furthermore, the inventors have developed three merit figures which allow to evaluate the quality of the MPPT OCC controller in terms of maximum power extracted from the photovoltaic field.

20 Moreover, on the basis of the aforementioned constraint equations and merit figures, the optimisation method developed by the inventors identifies the set of the OCC controller parameters that is optimal in order to delimit the region of maximum power point tracking (MPPT).

25 On the basis of the above, the inventors have developed a new control circuit integrating the conventional OCC analog circuit, shown in Figure 2, with a digital circuit that may implement the maximum power operation in static sunlight conditions, as well as the dynamic maximum power point tracking (MPPT), through the P&O technique, by operating on one of the setting parameters of the OCC controller for achieving a real maximum power point tracking of the photovoltaic field through dynamic adaptation to the instant conditions of the photovoltaic field operation as imposed by sunlight and temperature, preferably, but not exclusively, detected through the field voltage and current.

30 The result of the above is a single stage photovoltaic inverter device implemented through an OCC-MPPT integrated controller optimised in static and/or dynamic way, intended for applications of the

single-phase and three-phase type.

More in general, the single stage inverter device that is the subject matter of the invention, with OCC-MPPT, and possibly P&O, integrated control is capable to achieve in an automatic way, and possibly also dynamically, for any energy source, such as for instance fuel cells, batteries, and wind sources, specific operation conditions deemed to be preferential for the considered source.

In order to adequately choose the parameters  $K$ ,  $K_g$ ,  $V_c$ ,  $R_1$ ,  $C_1$ ,  $R_s$  and  $T_s$  of equation [7] for maximising the output power  $P_o$  of the inverter, i.e. of the photovoltaic field 1, the inventors have developed a new representation of the average power  $P_i$  at the inverter input as sum of the inverter internal losses  $P_{\text{InverterLosses}}$ , the average power  $P_{R_s}$  wasted by the sensing resistance  $R_s$ , and the average power  $P_o$  injected into the grid:

$$P_i = P_o + P_{R_s} + P_{\text{InverterLosses}} \quad [8]$$

By neglecting the internal losses  $P_{\text{InverterLosses}}$ , the losses due to  $R_s$  may lead to an expression useful for the aim of optimising the parameters:

$$P_{R_s} = R_s \cdot I_o^2 \quad [9]$$

from equations [7] and [8] and from equation [4] expressed in terms of effective values the following expression of the average power  $P_i$  at the inverter input is obtained:

$$P_i \cong P_o + R_s \cdot I_o^2 = V_o \cdot \frac{K \cdot V_o - V_m \cdot D}{R_s} + R_s \cdot \left( \frac{K \cdot V_o - V_m \cdot D}{R_s} \right)^2 \Rightarrow$$

$$P_i \cong \frac{V_o^2}{R_s} \cdot \left( K - \frac{V_m}{V_g} + K^2 + \frac{V_m^2}{V_g^2} - 4 \cdot K \frac{V_m}{V_g} \right) \quad [10]$$

The average voltage  $V_g$  of the photovoltaic field 1 is given by the following non linear constraint equation expressing the balance between the power  $P_g$  generated by the photovoltaic field 1 and the power  $P_i$  given by equation [10]:

$$P_i(V_g) = P_g(V_g) \quad (11)$$

The power  $P_g$  generated by the photovoltaic field 1 may be evaluated through the non linear model proposed by S. Liu and R.A. Dougal in "Dynamic multiphysics model for solar array", IEEE Transactions on Energy Conversion, Vol. 17, No. 2, June 2002, pp. 285-294, that provides the current  $I_g$  of the photovoltaic field 1 as a function of the voltage  $V_g$  of the photovoltaic field 1, of the temperature  $T$  of the panels, of

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the solar irradiance  $S$  and of the number of series-connected and parallel-connected panels constituting the field:

$$I_g = I_H - I_s \cdot \left( e^{\frac{V_g + R_{series} \cdot I_g}{\eta \cdot V_T}} - 1 \right) - \frac{V_g + R_{series} \cdot I_g}{R_{shunt}} \quad [12]$$

where  $R_{series}$  and  $R_{shunt}$  are series and shunt, respectively, parasitic resistances which depend on the number of panels and on their connection, besides on the type of panel,  $I_H$  is the light induced current depending on the solar irradiance  $S$  and on the panel temperature  $T$ ,  $\eta$  is the diode ideality factor schematising the photovoltaic field,  $I_s$  and  $V_T$  are respectively the saturation current and the thermal voltage, both depending on the panel temperature  $T$ .

For the correct operation of the OCC inverter, besides the constraints represented by equations [13] and [14], the effect of the oscillation, typically at a frequency of 120Hz/100Hz, of the voltage  $V_g$  of the photovoltaic field 1 caused by the grid 2 (as also illustrated by S. Baekhoej et al.) must be suitably considered. In particular, the control voltage  $V_c$  must meet the following constraint:

$$V_c > K_g (V_g + \Delta V_g) \quad [21]$$

where  $\Delta V_g$  is the peak-to-peak amplitude of the 120Hz/100Hz oscillation, that is represented by:

$$\Delta V_g = \frac{P_i}{\omega_{grid} V_g C_b} \quad (22)$$

where  $\omega_{grid}$  is the pulsation frequency of the grid 2 (in rad/s) and  $C_b$  is the capacitance of the buffer capacitor. The constraint of equation [21] ensures that the input voltage of the resettable integrator 9 of the OCC controller 19 of Figure 2 is always positive. If the constraint were violated, the consequent phase inversion at the output of the resettable integrator 9 would produce a control fault and a decay of the output PF-out power factor.

The inventors have defined a further constraint condition that allows to ensure an optimal behaviour of the inverter operating as double buck converter:

$$V_g - \Delta V_g > (1 + K) \cdot V_{o,max} \quad [23]$$

The constraint represented by equation [23] ensures that, at any

time instant, the input voltage of the bridge comprising the four switches M1-M4 is higher than its output voltage, taking account of the worst case occurring when the voltage of the photovoltaic field 1, affected by the ripple at frequency  $2f_{\text{grid}}$  (wherein  $f_{\text{grid}}$  is preferably equal to 50 Hz or 60 Hz) produced by the ac electric energy distribution network 2, assumes its minimum value  $(V_g - \Delta V_g)$  and the voltage drop on the sensing resistance  $R_s$  assumes its maximum value

$$R_s \cdot I_{o,\text{max}} = R_s \cdot K_1 \cdot V_{o,\text{max}} = K \cdot V_{o,\text{max}}$$

As said before, in order to obtain a robust PF-out control it is necessary that, at any level of solar irradiance  $S$  within the range of operation that is desired to ensure  $[S_{\text{min}}, S_{\text{max}}]$ , the OCC controller 19 is capable to correctly modulate the output current  $i_o(t)$  according to equation [4] and the average output power  $P_o$  according to equation [5], that is modulated by the term  $(K \cdot V_m / V_g)$  depending on the level of irradiance  $S$  through the term  $V_m / V_g$ . The oscillations of the voltage  $v_g(t)$  of the photovoltaic field 1 translates into a disturbance of the term  $V_m / V_g$  strongly affecting the waveform of the output current  $i_o(t)$  and the range of which the inventors have evaluated.

Starting from equation [6], the range of variation  $\left[ \frac{V_m}{V_g} \Big|_{\text{min}}, \frac{V_m}{V_g} \Big|_{\text{max}} \right]$  of the ratio  $V_m / V_g$  is defined by the following values:

$$\frac{V_m}{V_g} \Big|_{\text{min}} = \frac{V_c - K_g \cdot (V_g + \Delta V_g)}{V_g + \Delta V_g} \cdot \frac{T_s}{R_1 \cdot C_1} \quad [24]$$

$$\frac{V_m}{V_g} \Big|_{\text{max}} = \frac{V_c - K_g \cdot (V_g - \Delta V_g)}{V_g - \Delta V_g} \cdot \frac{T_s}{R_1 \cdot C_1} \quad [25]$$

For ensuring a high PF-out factor, the extreme values of  $V_m / V_g$  given by equations [24] and [25] must fall within an interval determined as a function of the deliverable photovoltaic power and of the maximum power that the inverter is capable to sustain. The upper bound  $P_{o,\text{max}}$  of the inverter output power is given by

$$P_{o,\text{max}} = K V_o^2 / R_s$$

For a correct operation of the photovoltaic conversion system, the inverter must be able to deliver a power  $P_o$  at least equal to the maximum power  $P_{g,\text{MPP}}(S_{\text{max}})$  deliverable by the photovoltaic field 1 in

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correspondence with the maximum sunlight level  $S=S_{\max}$  and at the corresponding voltage  $V_g$ :

$$\alpha \cdot P_{g,MPP}(S_{\max}) = K \frac{V_o^2}{R_s} \quad [26]$$

5 where the coefficient  $\alpha$  (with  $\alpha \geq 1$ ) expresses the inverter overloading capacity with respect to the maximum input power  $P_{g,MPP}(S_{\max})$  provided by the photovoltaic field 1. Equation [26] may be transformed in an explicit form with respect to the ratio  $V_m/V_g$  through equation [5]:

$$P_o = K \cdot \frac{V_o^2}{R_s} \cdot \left(1 - \frac{V_m}{V_g} \cdot \frac{1}{K}\right) = \alpha \cdot P_{g,MPP}(S_{\max}) \cdot \left(1 - \frac{V_m}{V_g} \cdot \frac{1}{K}\right) \quad (27)$$

and thus:

$$10 \quad \frac{V_m}{V_g} = K \cdot \left(1 - \frac{P_o}{\alpha \cdot P_{g,MPP}(S_{\max})}\right) \quad [28]$$

The ratio  $V_m/V_g$  expressed in equation [28] depends on the sunlight level  $S$  in correspondence with which the inverter output power  $P_o$  is evaluated and it allows to fix the range within which the extreme values given by equations [24] and [25] must be included:

$$15 \quad \left[ \frac{V_m}{V_g} \Big|_{\min}, \frac{V_m}{V_g} \Big|_{\max} \right] \subset K \cdot \left(1 - \frac{P_o}{\alpha \cdot P_{g,MPP}(S_{\max})}\right) \cdot [(1-\gamma), (1+\gamma)] \quad [29]$$

where the coefficient  $\gamma < 1$  defines the bounds allowed for the range of the ratio  $V_m/V_g$  determined by  $\Delta V_g$ , from which it is obtained:

$$K \left(1 - \frac{P_o(S)}{\alpha \cdot P_{g,MPP}(S_{\max})}\right) \cdot (1-\gamma) \leq \frac{V_m}{V_g} \Big|_{\min} \leq \frac{V_m}{V_g} \Big|_{\max} \quad [30-a]$$

$$\frac{V_m}{V_g} \Big|_{\min} \leq \frac{V_m}{V_g} \Big|_{\max} \leq K \left(1 - \frac{P_o(S)}{\alpha \cdot P_{g,MPP}(S_{\max})}\right) \cdot (1+\gamma) \quad [30-b]$$

20 The new constraints represented by equations [23] and [30] require, for the correct operation of a OCC single-stage photovoltaic inverter, the determination of a systematic solving method in order to find the set of values to assign to the characteristic parameters that allows to attain optimal performance. In particular, the characteristic parameters of  
25 the OCC inverter to determine are  $K$ ,  $K_g$ ,  $R_s$ ,  $V_o$ ,  $\tau$ , where  $\tau=R_1C_1$ ,

assuming the remaining parameters  $V_o$ ,  $T_s$ ,  $L$ ,  $C$ ,  $\omega_{\text{grid}}$  as fixed.

To this end, the inventors have developed three distinct merit figures providing, for each possible specific set of values of the characteristic parameters of the OCC inverter, a performance index in terms of power extracted from the photovoltaic field.

The first merit figure, referred to as " $\Psi_1$ ", represents the difference between the maximum power  $P_{g,MPP}(S_{\min})$  of the photovoltaic field 1 and the inverter output power  $P_o(S_{\min})$ , evaluated at the minimum sunlight level  $S_{\min}$  related to the range  $[S_{\min}, S_{\max}]$  of interest, and it is given by:

$$\Psi_1 = P_{g,MPP}(S_{\min}) - P_o(S_{\min}) \quad [31]$$

Specific sets of values of the characteristic parameters of the OCC inverter ensuring low values of such first merit figure  $\Psi_1$  are particularly adapted to attain a high photovoltaic conversion efficiency in places with high cloudiness level and hence low sunlight level  $S$ .

The second merit figure, referred to as " $\Psi_2$ ", represents the difference between the maximum power  $P_{g,MPP}(S_{\max})$  of the photovoltaic field and the inverter output power  $P_o(S_{\max})$  at the maximum sunlight level  $S_{\max}$  related to the range  $[S_{\min}, S_{\max}]$  of interest, and it is given by:

$$\Psi_2 = P_{g,MPP}(S_{\max}) - P_o(S_{\max}) \quad [32]$$

Specific sets of values of the characteristic parameters of the OCC inverter ensuring low values of such second merit figure  $\Psi_2$  are particularly adapted to attain high photovoltaic conversion efficiencies in places with low cloudiness level.

The third merit figure, referred to as " $\Psi_3$ ", represents the root mean square deviation of the maximum power  $P_{g,MPP}(S)$  of the photovoltaic field from the inverter output power  $P_o(S)$  over the whole range  $[S_{\min}, S_{\max}]$  of interest of the sunlight level  $S$ , discretised into  $N$  equally distributed levels:

$$\Psi_3 = \sqrt{\sum_{k=1}^N \frac{[P_{g,MPP}(S_k) - P_o(S_k)]^2}{P_{g,MPP}^2(S_k)}} \quad [33]$$

Specific sets of values of the characteristic parameters of the OCC inverter ensuring low values of such third merit figure  $\Psi_3$  are adapted to attain good photovoltaic conversion efficiency mean values.

The three merit figures  $\Psi_1$ ,  $\Psi_2$ , and  $\Psi_3$  may be used for a systematic exploration of the parameter space  $SP$ , implementable through

both deterministic and stochastic numerical techniques, suitable for different application contexts related to the range  $[S_{min}, S_{max}]$  of interest.

Figure 3 shows a first embodiment of the single stage inverter device according to the invention, that meets the constraints represented by equations [13], [14], [21], [23] and [30], and that further minimises the three merit figures  $\Psi_1$ ,  $\Psi_2$ , and  $\Psi_3$  represented by equations [31]-[33].

In particular, it may be observed that, similarly to the prior art device of Figure 2, the device of Figure 3 comprises four semiconductor power switches M1-M4 (preferably implemented through respective MOSFETs or IGBTs), the gate terminals of which are controlled by the controller 10. The controller 10 receives as inputs the voltage  $v_g(t)$  of the photovoltaic field 1, the ac voltage  $v_o(t)$  of the grid 2, and the value of the voltage drop on the resistor  $R_s$  sensing the inverter output current  $i_o(t)$ .

Specifically, the gate terminals of the four switches M1, M2, M3 and M4 are controlled so that, during the time interval in which the voltage of grid 2 presents positive values with respect to the polarity indicated in Figure 3, M4 is closed (i.e., conducting), M2 and M3 are open (i.e., not conducting) while M1 is being closed and open with period  $T_s$ , so that M1 is conducting during the first part of the switching period  $T_s$ , of length equal to the product of the switching duty-cycle multiplied by the switching period  $T_s$ , and vice versa M1 is off for a time equal to the remaining part of the switching period  $T_s$ ; vice versa, the gate terminals of the four switches M1, M2, M3 and M4 are controlled so that, during the time interval in which the voltage of grid 2 presents negative values with respect to the polarity indicated in Figure 3, M2 is closed (i.e. conducting), M4 and M1 are open (i.e., not conducting) while M3 is closed and open with period  $T_s$ , so that M3 is conducting during the first part of the switching period  $T_s$ , of length equal to the product of the switching duty-cycle multiplied by the switching period  $T_s$ , and vice versa M3 is off for a time equal to the remaining part of the switching period  $T_s$ .

The gate terminals of the switches M1, M2, M3 and M4 receive the corresponding control signals from a logic circuit 11 (by way of example implemented with two AND gate and an inverting NOT gate) that receives as inputs a signal of synchronisation with the voltage  $v_o(t)$  of the grid 2 and the signal of the direct output Q of a level-triggered SR-type flip-flop 12, the input S of which is connected to a clock generator 13 at frequency  $f_s=1/T_s$ . The input R of the flip-flop 12 receives the output signal of a

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comparator 14, the non inverting input of which receives the absolute value of the voltage drop on the sensing resistor  $R_s$  (i.e.  $|R_s \cdot i_o|$ ), and the inverting input of which receives the sum of the signal coming from the resettable integrator 9 and the absolute value of the voltage  $v_o(t)$  of the grid 2 (i.e.  $|K \cdot v_o| - v_m \cdot t / T_s$ , wherein  $v_m$  is expressed by equation [6]). In particular, the resettable integrator 9 (that is effectively reset by the complementary output  $\overline{Q}$  of the flip-flop 12, i.e. when  $|R_s \cdot i_o| > |K \cdot v_o| - v_m \cdot t / T_s$  and, hence, the output of the comparator 14 is high) integrates the difference (that is always a positive value, due to the [21]) between the voltage  $v_g$  of the photovoltaic field 1 and the control voltage  $V_c$ . In this way, the flip-flop 12 adjusts the duty cycle of the signals for controlling the gates of the switches M1-M4.

The device of Figure 3 has the following values of the parameters:  $C_b=3\text{mF}$ ;  $L=1.65\text{mH}$ ;  $V_o=110\text{Vrms}$ ; grid frequency  $f_{\text{grid}} = 60\text{Hz}$ ; inverter switching frequency  $f_s=33\text{kHz}$ , with switching period  $T_s=1/f_s$ ; the photovoltaic field 1 is composed by sixteen panels connected in series, each one with maximum power voltage within the range  $[14,16]\text{V}$ ; panel temperature equal to ambient temperature,  $T=310\text{K}$ ; voltage  $v_g$  of the photovoltaic field 1 at the inverter input belonging to the range  $[220,260]\text{V}$ ; peak voltage  $V_{o,\text{max}}$  of the inverter output voltage  $V_{o,\text{max}}=\sqrt{2} \cdot V_o \approx 156\text{V}$ ; saturation voltage of the operational amplifiers used for the integrator 9 and for making the adders and the sensors of the circuit 10  $V_{\text{op,sat}}=24\text{V}$ ;  $\alpha=1.3$ ;  $\gamma=0.05$ .

The search space  $SP$  of the set of the values of the parameters is defined in Table I. The search range for the sensing resistance  $R_s$  is defined so as to prevent saturation phenomena of the operational amplifiers.

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| K                                             | K <sub>g</sub>                                | R <sub>s</sub> [Ω]                                                                       |
|-----------------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------------|
| [0, V <sub>op,sat</sub> /V <sub>o,max</sub> ] | [0, V <sub>op,sat</sub> /V <sub>g,max</sub> ] | {0, (V <sub>op,sat</sub> ·V <sub>o</sub> )/[√2 /P <sub>g.MPP</sub> (S <sub>max</sub> )]} |
| [0, 0.15]                                     | [0, 0.07]                                     | [0, 1.965]                                                                               |

| V <sub>c</sub> [V]        | τ=R <sub>1</sub> C <sub>1</sub> [μs]    | S [W/m <sup>2</sup> ]                  |
|---------------------------|-----------------------------------------|----------------------------------------|
| [0, V <sub>op,sat</sub> ] | [0.01·T <sub>s</sub> , T <sub>s</sub> ] | [S <sub>min</sub> , S <sub>max</sub> ] |
| [0, 24]                   | [0.3, 30.3]                             | [100, 1000]                            |

Table I

5                    Figure 4 shows the power curves of the photovoltaic field 1  
corresponding to ten levels of sunlight S, and the three operation curves  
P<sub>o</sub>(V<sub>g</sub>) of the photovoltaic OCC inverter corresponding to the three sets of  
values of the design parameters ensuring the minimum values of the three  
merit figures Ψ<sub>1</sub>, Ψ<sub>2</sub>, and Ψ<sub>3</sub>, obtained after an estimation with the  
10                    Montecarlo method with 2·10<sup>5</sup> trials for each one of the three merit figures  
described above. Table II summarises the values of the parameters  
corresponding to the three design solutions which minimise the three merit  
figures Ψ<sub>1</sub>, Ψ<sub>2</sub>, and Ψ<sub>3</sub> and the corresponding power levels obtained at  
maximum and minimum sunlight.

15                    As expected, the inverter characteristic curve P<sub>o</sub>(V<sub>g</sub>) obtained by  
minimising the first merit figure Ψ<sub>1</sub> corresponds to an design solution that  
is unsatisfactory at high levels of sunlight S, while the other two solutions  
present better, although not optimal, performance.

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|                            | <b>K</b> | <b>K<sub>g</sub></b> | <b>R<sub>s</sub> [<math>\Omega</math>]</b> |
|----------------------------|----------|----------------------|--------------------------------------------|
| <b><math>\Psi_1</math></b> | 0.036405 | 0.0013691            | 0.36847                                    |
| <b><math>\Psi_2</math></b> | 0.031513 | 0.0096176            | 0.30655                                    |
| <b><math>\Psi_3</math></b> | 0.024794 | 0.0528300            | 0.24229                                    |

|                            | <b>V<sub>c</sub> [V]</b> | <b>R<sub>1</sub>C<sub>1</sub> [<math>\mu</math>s]</b> | <b>Output Power [W]</b>                      |                                             |
|----------------------------|--------------------------|-------------------------------------------------------|----------------------------------------------|---------------------------------------------|
| <b><math>\Psi_1</math></b> | 5.4465                   | 20.188                                                | P <sub>o</sub> (S <sub>max</sub> ) = 309.856 | P <sub>o</sub> (S <sub>min</sub> ) = 91.832 |
| <b><math>\Psi_2</math></b> | 3.4271                   | 10.660                                                | P <sub>o</sub> (S <sub>max</sub> ) = 794.108 | P <sub>o</sub> (S <sub>min</sub> ) = 76.932 |
| <b><math>\Psi_3</math></b> | 15.7446                  | 29.394                                                | P <sub>o</sub> (S <sub>max</sub> ) = 769.943 | P <sub>o</sub> (S <sub>min</sub> ) = 89.970 |

Table II

5           The waveforms of the inverter output currents, compared with the reference waveform of the grid voltage, shown in Figure 5, obtained through circuit simulation performed by using the software PSIM<sup>®</sup>, shows the high PF-out attained at both high and low levels of sunlight S (respectively, Fig. 5a and Fig. 5b) with the set of parameter values  
10           minimising the second merit figure  $\Psi_2$ .

          The solutions summarised in Table II may be improved if a larger number of trials in the Montecarlo method is used. For instance, with  $8 \cdot 10^5$  trials, the solutions summarised in Table III are obtained, while Figure 6 shows the corresponding three operation curves P<sub>o</sub>(V<sub>g</sub>) of the photovoltaic  
15           OCC inverter (superimposed on the power curves of the photovoltaic field 1 corresponding to ten levels of sunlight S), and Figure 7 shows the simulated waveforms of the inverter output currents, compared with the reference waveform of the grid voltage, corresponding to the set of parameter values minimising the second merit figure  $\Psi_2$  (Fig. 7a for high  
20           sunlight levels and Fig. 7b for low levels of sunlight S).

          As expected, the maximum output powers are higher with respect to the preceding case for each one of the three optimal solutions

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determined with the three merit figures.

|                      | <b>K</b> | <b>K<sub>g</sub></b> | <b>Rs [Ω]</b> |
|----------------------|----------|----------------------|---------------|
| <b>Ψ<sub>1</sub></b> | 0.023410 | 0.0056853            | 0.21366       |
| <b>Ψ<sub>2</sub></b> | 0.056368 | 0.0577370            | 0.55243       |
| <b>Ψ<sub>3</sub></b> | 0.031339 | 0.049305             | 0.30907       |

|                      | <b>V<sub>c</sub> (V)</b> | <b>R<sub>1</sub>C<sub>1</sub><br/>[μs]</b> | <b>Output power [W]</b>                        |                                                 |
|----------------------|--------------------------|--------------------------------------------|------------------------------------------------|-------------------------------------------------|
| <b>Ψ<sub>1</sub></b> | 4.6276                   | 20.901                                     | P <sub>o</sub> (S <sub>max</sub> )<br>419.7095 | = P <sub>o</sub> (S <sub>min</sub> )<br>92.0455 |
| <b>Ψ<sub>2</sub></b> | 16.0471                  | 20.571                                     | P <sub>o</sub> (S <sub>max</sub> )<br>887.4122 | = P <sub>o</sub> (S <sub>min</sub> )<br>76.8944 |
| <b>Ψ<sub>3</sub></b> | 14.7741                  | 25.555                                     | P <sub>o</sub> (S <sub>max</sub> )<br>791.5862 | = P <sub>o</sub> (S <sub>min</sub> )<br>87.3512 |

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Table III

The inventors have attained further improvements by using evolutionary type search algorithms, such as for instance genetic algorithms. In this regard, Table IV summarises the values of the optimal sets of parameters minimising the second merit figure  $\Psi_2$  obtained by means of the two previous Montecarlo methods and the values of the set obtained through the known genetic algorithm Genocop, while Figure 8 shows the corresponding operation curves  $P_o(V_g)$  of the photovoltaic OCC inverter.

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|                                   | <b>K</b> | <b>K<sub>g</sub></b> | <b>R<sub>s</sub> [<math>\Omega</math>]</b> |
|-----------------------------------|----------|----------------------|--------------------------------------------|
| <b>2·10<sup>5</sup> MC trials</b> | 0.031513 | 0.0096176            | 0.30655                                    |
| <b>8·10<sup>5</sup> MC trials</b> | 0.056368 | 0.0577370            | 0.55243                                    |
| <b>Genetic algorithm</b>          | 0.031161 | 0.01327885           | 0.305412                                   |

|                                   | <b>V<sub>c</sub> [V]</b> | <b>R<sub>1</sub>C<sub>1</sub><br/>[<math>\mu</math>s]</b> | <b>Output<br/>power [W]</b>                      |
|-----------------------------------|--------------------------|-----------------------------------------------------------|--------------------------------------------------|
| <b>2·10<sup>5</sup> MC trials</b> | 3.4271                   | 10.660                                                    | P <sub>o</sub> (S <sub>max</sub> ) =<br>794.1080 |
| <b>8·10<sup>5</sup> MC trials</b> | 16.0471                  | 20.571                                                    | P <sub>o</sub> (S <sub>max</sub> ) =<br>887.4122 |
| <b>Genetic algorithm</b>          | 3.6291                   | 9.570                                                     | P <sub>o</sub> (S <sub>max</sub> ) =<br>916.5764 |

Table IV

5                    Figure 9 shows the simulated waveforms (for high and low levels of sunlight S, respectively in Fig. 9a and 9b) of the inverter output currents, compared with the reference waveform of the grid voltage, corresponding to such set of the parameter values obtained through genetic optimisation, which show the high PF-out factor with an extremely low percentage value of total harmonic distortion, equal to THD%=3.5178.

10                   Figures 10 and 11 instead show the simulated dynamic behaviour of the inverter corresponding to such set of the parameter values obtained through genetic optimisation in the maximum power point tracking in presence of sunlight S variable during a time interval equal to about 20 seconds. In particular: Figure 10a shows the inverter output current, compared with reference waveform of the grid voltage, in correspondence

with the sub-interval of time ranging from 11.5 seconds to 11.6 seconds; Figure 10b shows a comparison between output power  $P_o$  effectively obtained from the photovoltaic field 1 and the maximum power deliverable from the same field 1 (real maximum power point) during the whole time interval (from the initial instant  $t=0$  to the instant equal to about 22 seconds); Figure 11 shows the corresponding shift, during the same time interval, of the operation point over the inverter output power-voltage characteristic curves.

In order to point out the fundamental contribution of the new constraints, in particular of that represented by equation [30], the inventors have carried out a test searching the set of inverter parameter values related to the minimisation of the second merit figure  $\Psi_2$  without the constraint [30]. Two sets of obtained parameter values are summarised in Table V and in Table VI. Each one of Figures 12 and 13 shows the two simulated waveforms (figures a) and b), respectively) of the output current  $i_o(t)$  (compared with the reference waveform of the grid voltage) and of the inverter average output power  $P_o$  (compared with the maximum power of the photovoltaic field 1), in conditions of maximum sunlight  $S_{max}$ , having the sets of the parameters of Table V (Figure 12) and Table VI (Figure 13).

|                            | <b>K</b> | <b>K<sub>g</sub></b> | <b>R<sub>s</sub> [<math>\Omega</math>]</b> |
|----------------------------|----------|----------------------|--------------------------------------------|
| <b><math>\Psi_2</math></b> | 0.094218 | 0.0070186            | 0.0063001                                  |

|                            | <b>V<sub>c</sub> [V]</b> | <b>R<sub>1</sub>C<sub>1</sub> [<math>\mu</math>s]</b> | <b>Output power [W]</b>                          |                                                 |
|----------------------------|--------------------------|-------------------------------------------------------|--------------------------------------------------|-------------------------------------------------|
| <b><math>\Psi_2</math></b> | 13.8066                  | 17.95                                                 | P <sub>o</sub> (S <sub>max</sub> ) =<br>948.7253 | P <sub>o</sub> (S <sub>min</sub> ) =<br>91.9232 |

Table V

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|                            | <b>K</b>  | <b>K<sub>g</sub></b> | <b>R<sub>s</sub> [<math>\Omega</math>]</b> |
|----------------------------|-----------|----------------------|--------------------------------------------|
| <b><math>\Psi_2</math></b> | 0.0084562 | 0.061429             | 0.046981                                   |

|                            | <b>V<sub>c</sub> (V)</b> | <b>R<sub>1</sub>C<sub>1</sub> [<math>\mu</math>s]</b> | <b>Output power [W]</b>                       |                                              |
|----------------------------|--------------------------|-------------------------------------------------------|-----------------------------------------------|----------------------------------------------|
| <b><math>\Psi_2</math></b> | 14.7295                  | 21.95                                                 | P <sub>o</sub> (S <sub>max</sub> ) = 939.5787 | P <sub>o</sub> (S <sub>min</sub> ) = 91.7853 |

Table VI

5 It should be noted that in Figure 12 the value of the inverter  
average output power  $P_0$  scaled by using the results summarised in Table  
V at the maximum level of sunlight  $S=S_{max}$  in Figure 12b is very close to  
the maximum power  $P_{g,MPP}(S_{max})$  of the photovoltaic field 1, but the  
distortion level of the current of Figure 12a is practically inadmissible  
10 (THD% = 31.4). Vice versa, Figure 13 shows that the inverter scaled by  
using the results summarised in Table VI provides an average output  
power  $P_0$  (see Figure 13b) significantly lower than the photovoltaic  
maximum  $P_{g,MPP}(S_{max})$ , against a better PF out (see Figure 13a).

15 This shows that the fulfilment of constraint [30] is generally  
indispensable for simultaneously attaining high output powers  $P_0$  and high  
PF-out.

20 The inventors have carried out a similar test in relation to the  
constraint represented by equation [14]. Figure 14 shows the waveforms  
of the two inputs of the comparator 14 of Figure 3 in cases of violation  
(Figure 14a) and of fulfilment (Figure 14b) of the constraint [14]: in the first  
case, the phase inversion of the voltage at the non inverting input terminal  
of the comparator 14 does not allow the periodic operation at fixed  
switching frequency  $f_s$ , instead occurring in the second case, and it  
determines a strong distortion of the output current  $i_o(t)$ , as shown in  
25 Figure 15.

Differently from what proposed by Chen and Smedley, the device  
developed by the inventors is not scaled so as to meet the following  
constraint:

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$$V_m > K \frac{V_{o,max}}{D_{max}} \quad (34)$$

where  $D_{max}$  is the maximum value of the duty-cycle admissible for the circuit.

5 In fact, while such constraint is necessary in the device proposed by Chen and Smedley for ensuring the existence of the conditions for resetting the integrator 9 of Figure 2 in every switching cycle, even if the output current  $i_o(t)$  is equal to zero, in the device according to the invention the above is ensured by the use of the level-triggered flip-flop 12 of Figure 3. Furthermore, it is preferable that the determination of the set of  
10 parameters of the device according to the invention does not include the constraint [34], since otherwise the device shows performance considerably lower, especially in terms of fall of the output power  $P_0$ .

In particular, Table VII shows the set of parameters obtained after an estimation with the Montecarlo method with  $8 \cdot 10^5$  trials for each one of  
15 the three merit figures described above and including the constraint [34].

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|          | K        | $K_g$    | $R_s [\Omega]$ |
|----------|----------|----------|----------------|
| $\Psi_1$ | 0.029192 | 0.016054 | 0.28945        |
| $\Psi_2$ | 0.069325 | 0.011318 | 0.65468        |
| $\Psi_3$ | 0.069325 | 0.011318 | 0.65468        |

|          | $V_c (V)$ | $R_1 C_1 [\mu s]$ | Output power [W]          |                          |
|----------|-----------|-------------------|---------------------------|--------------------------|
| $\Psi_1$ | 9.6104    | 30.037            | $P_o(S_{max}) = 430.0164$ | $P_o(S_{min}) = 92.0269$ |
| $\Psi_2$ | 10.953    | 22.043            | $P_o(S_{max}) = 538.4387$ | $P_o(S_{min}) = 82.871$  |
| $\Psi_3$ | 10.953    | 22.043            | $P_o(S_{max}) = 538.4387$ | $P_o(S_{min}) = 82.871$  |

Table VII

5 Figure 16 shows the output power-voltage characteristic curves of the inverter with the set of the parameter values of Table VII minimising the merit figures  $\Psi_1$ ,  $\Psi_2$ ,  $\Psi_3$  while Figures 17a and 17b show the simulated waveform, respectively, of the output current  $i_o(t)$  of such inverter (compared with the reference waveform of the grid voltage) and of the inverter output power  $P_o$  (compared with the maximum power of the photovoltaic field 1), under conditions of maximum sunlight  $S=S_{max}$  with the set of the parameter values of Table VII minimising the merit figure  $\Psi_2$ . It may be observed that while the PF-out level is good, the level of extracted power  $P_o$  is significantly lower than the maximum value deliverable by the photovoltaic field 1, that is on the contrary substantially obtainable by eliminating the constraint [34].

The photovoltaic single stage inverter device shown in Figure 3

allows to attain a significant improvement in terms of performance both for the power part and for the control part, at low cost, since the controller 10 is implementable through analog circuitry with parameters optimised through the described process imposing the constraints represented by equations [13], [14], [21], [23] and [30], and minimising the three merit figures  $\Psi_1$ ,  $\Psi_2$ , and  $\Psi_3$  represented by equations [31]-[33].

The operation point of the inverter device of Figure 3 in terms of output power as a function of the voltage  $v_g(t)$  of the photovoltaic field 1 remains moving along a fixed path, identified by the set of parameters  $\{K, K_g, R_s, V_c, \tau\}$ , intersecting the maximum power point of the photovoltaic field only in particular environmental conditions, remaining in the proximity of it in the other cases, at a distance depending on the level of instant sunlight  $S$  and on the instant temperature  $T$ . This is inevitable because there is no design solution with a set of fixed values of the parameters  $\{K, K_g, R_s, V_c, \tau\}$  ensuring that the inverter output power characteristic curve overlaps the locus of the maximum power points of the photovoltaic field under the variation of the sunlight  $S$  and the temperature  $T$  of the panels within their respective range of operation values  $[S_{\min}, S_{\max}]$  and  $[T_{\min}, T_{\max}]$ .

With reference to Figure 18, a second embodiment of the device according to the invention integrates in a different controller 20 the analog controller 10 of Figure 3 with a digital unit 21, achieving a function of the perturb and observe or P&O type and operating on the OCC controller parameters in order to attain the real maximum power point tracking MPPT.

In general, the P&O MPPT technique perturbs the operation voltage  $v_g(t)$  of the photovoltaic field 1 according to the so called hill climbing method. According to such method, the voltage  $v_g(t)$  is perturbed in a given direction (i.e., by either increasing or decreasing it), through a variation of the duty-cycle value of the inverter of the converter connected with its input to the photovoltaic field 1 and with its output to the grid 2. The instant output voltage and current of the photovoltaic field 1 are detected by the digital unit 21 that evaluates their product (i.e., the field output electric power): if this is higher than that detected after the last preceding perturbation, then the voltage  $v_g(t)$  is furthermore varied in the same direction, otherwise the direction of perturbation of the voltage  $v_g(t)$  is reversed.

In the device of Figure 18, the P&O MPPT technique is applied to the perturbation of the sole parameter  $V_c$ , that along with the other ones determine the behaviour of the inverter output power  $P_0$  curve, thus making such curve dynamic and in this way achieving the possibility of obtaining an intersection between the aforesaid curve and the characteristic curve of the photovoltaic field power  $P_g$  in correspondence with the maximum power point MPP, in any conditions of sunlight  $S$  and panel temperature  $T$ .

However, other embodiments of the device according to the invention may apply the P&O MPPT technique to the perturbation of one or more of the five parameters ( $K$ ,  $K_g$ ,  $R_s$ ,  $V_c$ ,  $\tau$ ) of the inverter or of any combination of two or more of them.

The efficiency of the P&O MPPT technique may be maximised by suitably setting the period  $T_a$  of sampling the voltage  $v_g(t)$  and the current  $i_g(t)$  of the photovoltaic field 1 (with  $T_a > T_s$ ) and the amplitude  $\Delta d$  of the duty-cycle perturbation. The sampling period  $T_a$  must be chosen as a function of the dynamics of the whole system given by the assembly constituted by the photovoltaic field 1 and the converter comprising the inverter, in order to avoid mistakes in MPPT tracking. The correct setting of duty-cycle perturbation amplitude  $\Delta d$  also prevents the operating point of the photovoltaic field 1 from oscillating around the MPP maximum power point, and allows to optimise the response speed of the controller 20 under fast variations of sunlight  $S$ .

In particular, the device of Figure 18 has as set of starting parameter values the one summarised in Table IV obtained through the known genetic algorithm Genocop, the digital unit 21 operating according to the illustrated P&O MPPT technique determining subsequent variations of the control voltage  $V_c$  within the range 3.4091 V to 5.0489 V, fulfilling constraint equations [13], [14], [21], [23], and [30].

The locus of operation points corresponding to the inverter output power  $P_0$  obtainable by making the voltage  $V_c$  vary within the range indicated above is shown in Figure 19, and it is in fact represented by the surface delimited by the two extreme curves corresponding to the two minimum and maximum values  $V_{c\_min}$  and  $V_{c\_max}$  of the voltage  $V_c$ . Such surface includes all the possible MPP maximum power points of the photovoltaic field 1 within the range of considered values of sunlight  $S$  (belonging to the range  $100 \text{ W/m}^2$  to  $1000 \text{ W/m}^2$ ).

The circuit of Figure 18 is optimised, in terms of values of the sampling period  $T_a$  and of the amplitude  $\Delta V_c$  of the perturbation of the voltage  $V_c$  (i.e. of the amplitude  $\Delta d$  of the perturbation of the inverter duty-cycle  $d(t)$ ) by applying the criteria indicated by N. Femia, G. Petrone, G. Spagnuolo, M. Vitelli, in the two papers "*Optimizing Sampling Rate of P&O MPPT Technique*" and "*Optimizing Duty-cycle Perturbation of P&O MPPT Technique*", presented at the Proc. of IEEE Power Electronics Specialist Conference, June 2004, Aachen (Germany), pp. 1945-1949, and pp. 1939-1944, respectively, approximately obtaining  $T_a=0.1$  s,  $\Delta V_c=0.2$  V.

Figure 20 compares the output power  $P_0$  of the P&O MPPT OCC photovoltaic inverter of Figure 18, having panel temperature equal to the ambient temperature  $T=310$  K, sunlight level  $S=1000$  W/m<sup>2</sup>, obtainable in the case when the values of the sampling period  $T_a$  and of the perturbation amplitude  $\Delta V_c$  are optimal  $\{T_a, \Delta V_c\}=\{0.1$  s, 0.2 V $\}$  and in the case when they are not optimal  $\{T_a, \Delta V_c\} = \{0.02$  s, 0.1 V $\}$ , with the maximum power available from the photovoltaic field 1. Figure 21 shows the corresponding behaviours of the respective control voltages  $V_c$ . The better performance of the optimal case is self-evident.

Figure 22 shows the dynamic performance of the P&O MPPT OCC photovoltaic inverter of Figure 18 with  $\{T_a, \Delta V_c\}=\{0.1$  s, 0.2 V $\}$ , for  $T=310$  K, under conditions of variable sunlight (Fig. 22a), showing the consequent time behaviours of the output power  $P_0$  (compared with the similarly variable maximum power available from the photovoltaic field 1, Figure 22b), and of the control voltage  $V_c$  (Fig. 22c).

Figure 23 shows the waveform of the output current  $i_o(t)$  (compared with the reference waveform of the grid voltage 2, Fig. 23a) and the time behaviour of the control voltage  $V_c$  (Fig. 23b) in a time sub-interval of Figure 22 ranging from 12.67 s to 12.73 s (wherein the control voltage  $V_c$  is subjected to a variation), from which it is evident that the quality of the waveform of the output current  $i_o(t)$  is maintained thanks to the presence of the P&O MPPT control.

Figure 24 shows the time behaviours of the output power  $P_0$  (compared with the maximum power available from the photovoltaic field 1, Figure 24a), and of the control voltage  $V_c$  (Fig. 24b) in presence of combined variations of sunlight  $S$  and panel temperature  $T$ . The very high inverter performance in terms of maximum power point tracking MPPT are evident.

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In particular, the comparison of the diagrams of Figures 10, 22, and 24 shows that the photovoltaic single stage inverter device according to the invention has optimal performance in terms of both MPPT and PF-out, not attainable by applying prior art devices.

5           The present invention has been described, by way of illustration and not by way of limitation, according its preferred embodiment, but it should be understood that those skilled in the art can make variations and/or changes, without so departing from the related scope of protection, as defined by the enclosed claims.

10

## CLAIMS

1. Single stage inverter device, for converters of power from dc energy sources (1) to an electric ac network or grid (2) having at least one phase, of pulsation frequency  $\omega_{\text{grid}}$ , comprising switching means (M1-M4) capable to periodically connect, with period  $T_s$  lower than the period  $T_{\text{grid}}$  corresponding to the pulsation frequency  $\omega_{\text{grid}}$ , a source (1), capable to output a voltage  $v_g(t)$  of average value  $V_g$ , to the grid (2) so that the device output current  $i_o(t)$  is in phase with the voltage  $v_o(t)$  of at least one phase of the grid (2), the maximum value of which is  $V_{o,\text{max}}$ , the switching means (M1-M4) being controlled by controlling electronic means (10, 20) operating according to a control over a single switching cycle of the switching means (M1-M4), the device seeing an output inductance  $L$ , the device comprising a sensing resistor of resistance  $R_s$  connected in series to the grid (2), the controlling electronic means (10, 20) comprising:
- 15 - a resettable integrator circuit (9) having a time constant  $\tau$  such that  $\tau < T_s$ , the input of which receives a voltage signal  $(V_c - K_g \cdot v_g)$  equal to the difference between a control voltage  $V_c$  and a voltage proportional by a first factor  $K_g$  to the output voltage  $v_g(t)$  of the source (1),
  - 20 - comparator means (14), capable to output a signal indicative of the comparison of a voltage drop  $[R_s \cdot i_o(t)]$  on the sensing resistor with the sum of the output signal of the integrator circuit (9) and a voltage  $[K \cdot v_o(t)]$  proportional by a second factor  $K$  to the voltage  $v_o(t)$  of the grid (2), and
  - 25 - generator means (11, 12, 13) capable to receive the output signal from the comparator means (14) and a signal indicative of the phase of the grid (2) for providing one or more signals for controlling the switching means (M1-M4),

the control voltage  $V_c$  and the first factor  $K_g$  being such to fulfil the following first constraint:

$$V_c \geq K_g V_g + \frac{(2V_{o,\text{max}} - V_g)R_s\tau}{2L},$$

the device being characterised in that it fulfils a second constraint whereby the input signal of the integrator circuit (9) is always positive, in that it fulfils a third constraint whereby, at any time instant, the input voltage of the switching means (M1-M4) is higher than the output voltage thereof, and in that it fulfils a fourth constraint whereby

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$$K \left( 1 - \frac{P_o(S)}{\alpha \cdot P_{g,MPP}(S_{max})} \right) \cdot (1 - \gamma) \leq \frac{V_m}{V_g} \Big|_{min} \leq \frac{V_m}{V_g} \Big|_{max}$$

$$\frac{V_m}{V_g} \Big|_{min} \leq \frac{V_m}{V_g} \Big|_{max} \leq K \left( 1 - \frac{P_o(S)}{\alpha \cdot P_{g,MPP}(S_{max})} \right) \cdot (1 + \gamma)$$

where:

$$- v_m = \left( \frac{V_c - K_g \cdot v_g}{\tau} \right) \cdot T_s$$

- 5                    -  $P_o(S)$  is the device output average power for a set  $S$  of operation conditions,
- $P_{g,MPP}(S_{max})$  is the maximum power deliverable by the source (1),
- $\alpha$  is a first coefficient of overload, with  $\alpha \geq 1$ , and
- $\gamma$  is a second coefficient, with  $\gamma < 1$ .

- 10                  2. Device according to claim 1, characterised in that the control voltage  $V_c$  and the first factor  $K_g$  are such that:

$$V_c > K_g (V_g + \Delta V_g)$$

where  $\Delta V_g$  is the peak-to-peak amplitude of the oscillation of the voltage  $v_g(t)$ .

- 15                  3. Device according to claim 1 or 2, characterised in that the second factor  $K$  is such that:

$$V_g - \Delta V_g > (1 + K) \cdot V_{o,max}$$

where  $\Delta V_g$  is the peak-to-peak amplitude of the oscillation of the voltage  $v_g(t)$ .

- 20                  4. Device according to any one of claims 1 to 3, characterised in that the resettable integrator circuit (9) is reset when  $|R_s \cdot i_o| > |K \cdot v_o| - v_m \cdot t / T_s$ .

5. Device according to any one of claims 1 to 4, characterised in that the controlling electronic means (10, 20) further comprises processing electronic means (21), connected at its input to the source (1) for determining the power thereof with sampling period  $T_a$ , capable to output at least one signal capable to vary the value of at least one corresponding parameter, selected from the group comprising the resistance  $R_s$ , the time constant  $\tau$ , the control voltage  $V_c$ , the first factor  $K_g$ ,  
25  
30                  the second factor  $K$ , and a combination of them, by continuously

perturbing the output average power  $P_o(S)$  so as to search the maximum output power point according to the so called hill climbing method.

5 6. Device according to claim 5, characterised in that the processing electronic means (21) is capable to detect the instant output voltage and current of the source (1).

7. Device according to claim 5 or 6, characterised in that  $T_a > T_s$ .

8. Device according to any one of claims 5 to 7, characterised in that the processing electronic means (21) outputs the control voltage  $V_c$ , that is provided as input to the integrator circuit (9).

10 9. Device according to any one of claims 1 to 8, characterised in that the controlling electronic means (10, 20) are at least partially integrated in at least one microprocessor and/or at least one digital signal processor and/or at least one microcontroller.

15 10. Device according to any one of claims 1 to 9, characterised in that the source (1) is such that the point of maximum input power of the device is variable and/or the factor of output power or PF-out of the device is variable with the set S of operation conditions.

11. Device according to claim 10, characterised in that the source (1) is a renewable energy source.

20 12. Device according to claim 11, characterised in that the source (1) is a photovoltaic source, the operation conditions of the set S being one or more conditions selected from the group comprising sunlight level, temperature, and source degradation.

25 13. Device according to any one of claims 1 to 12, characterised in that the electric network (2) is a single-phase or three-phase network.

30 14. Single switching cycle method of controlling switching means (M1-M4) of a single stage inverter device, for converters of power from dc energy sources (1) to an electric ac network or grid (2) having at least one phase, of pulsation frequency  $\omega_{grid}$ , wherein the switching means (M1-M4) periodically connects, with period  $T_s$  lower than the period  $T_{grid}$  corresponding to the pulsation frequency  $\omega_{grid}$ , a source (1), capable to output a voltage  $v_g(t)$  of average value  $V_g$ , to the grid (2) so that the device output current  $i_o(t)$  of each phase is in phase with the voltage  $v_o(t)$  of the same phase of the grid (2) the maximum value of which is  $V_{o,max}$ , the method comprising the following steps:

35 A. integrating, according to a time constant  $\tau$  such that  $\tau < T_s$ , a voltage

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signal  $(V_c - K_g \cdot v_g)$  equal to the difference between a control voltage  $V_c$  and a voltage proportional by a first factor  $K_g$  to the output voltage  $v_g(t)$  of the source (1),

- 5 B. comparing a voltage drop  $[R_s \cdot i_o(t)]$ , on a sensing resistor of resistance  $R_s$  connected in series to the grid (2), with the sum of the result of the integration of step A with a voltage  $[K \cdot v_o(t)]$  proportional by a second factor  $K$  to the voltage  $v_o(t)$  of the grid (2), and
- 10 C. generating one or more signals for controlling the switching means (M1-M4) on the basis of the result of the comparison of step B, the control voltage  $V_c$  and the first factor  $K_g$  being such to fulfil the following first constraint:

$$V_c \geq K_g V_g + \frac{(2V_{o,\max} - V_g) R_s \tau}{2L},$$

15 where  $L$  is the output inductance seen by the inverter device, the method being characterised in that the voltage signal integrated in step A is always positive, in that the input voltage of the switching means (M1-M4) is higher than the output voltage thereof, and in that

$$K \left( 1 - \frac{P_o(S)}{\alpha \cdot P_{g,MPP}(S_{\max})} \right) \cdot (1 - \gamma) \leq \frac{V_m}{V_g} \Big|_{\min} \leq \frac{V_m}{V_g} \Big|_{\max}$$

$$\frac{V_m}{V_g} \Big|_{\min} \leq \frac{V_m}{V_g} \Big|_{\max} \leq K \left( 1 - \frac{P_o(S)}{\alpha \cdot P_{g,MPP}(S_{\max})} \right) \cdot (1 + \gamma)$$

where:

- 20 -  $v_m = \left( \frac{V_c - K_g \cdot v_g}{\tau} \right) \cdot T_s$
- $P_o(S)$  is the device output average power for a set  $S$  of operation conditions,
  - $P_{g,MPP}(S_{\max})$  is the maximum power deliverable by the source (1),
  - $\alpha$  is a first coefficient of overload, with  $\alpha \geq 1$ , and
  - 25 -  $\gamma$  is a second coefficient, with  $\gamma < 1$ .

15. Method according to claim 14, characterised in that the control voltage  $V_c$  and the first factor  $K_g$  are such that:

$$V_c > K_g (V_g + \Delta V_g)$$

30 where  $\Delta V_g$  is the peak-to-peak amplitude of the oscillation of the voltage  $v_g(t)$ .

16. Method according to claim 14 or 15, characterised in that the

second factor K is such that:

$$V_g - \Delta V_g > (1 + K) \cdot V_{o,max}$$

where  $\Delta V_g$  is the peak-to-peak amplitude of the oscillation of the voltage  $v_g(t)$ .

5            17. Method according to any one of claims 14 to 15, characterised in that the result of the integration of step A is reset when  $|R_s \cdot i_o| > |K \cdot v_o| - v_m \cdot t / T_s$ .

10            18. Method of scaling an inverter device according to any one of claims 1 to 13, characterised in that the values of the resistance  $R_s$ , of the time constant  $\tau$ , of the control voltage  $V_c$ , of the first factor  $K_g$ , and of the second factor K are such to minimise at least one merit figure selected from the group comprising:

- a merit figure  $\Psi_0$ , equal to

$$\Psi_0 = P_{g,MPP}(S_0) - P_o(S_0)$$

15            where  $S_0$  is a set S of specific operation conditions and  $P_g(S_0)$  is the power delivered by the source in correspondence of the set  $S_0$  of specific operation conditions, and

- a further merit figure  $\Psi_3$ , equal to the root mean square deviation of the maximum power  $P_{g,MPP}(S)$  deliverable by the source (1) and the device output power  $P_o(S)$  over a whole range  $[S_{min}, S_{max}]$  of sets S of operation conditions, that is

$$\Psi_3 = \sqrt{\sum_{k=1}^N \frac{[P_{g,MPP}(S_k) - P_o(S_k)]^2}{P_{g,MPP}^2(S_k)}}$$

25            where  $S_{min}$  and  $S_{max}$  are sets of specific operation conditions whereby  $P_{g,MPP}(S)$  assumes, respectively, the minimum and the maximum value within the range  $[S_{min}, S_{max}]$ .

             19. Method according to claim 18, characterised in that the merit figure  $\Psi_0 = \Psi_1$  is calculated for the set  $S_{min}$  of specific operation conditions.

30            20. Method according to claim 18 or 19, characterised in that the merit figure  $\Psi_0 = \Psi_2$  is calculated for the set  $S_{max}$  of specific operation conditions.

             21. Method according to any one of claims 18 to 20, characterised in that the values of the resistance  $R_s$ , of the time constant  $\tau$ , of the control voltage  $V_c$ , of the first factor  $K_g$ , and of the second factor K are determined through at least one either deterministic and stochastic numerical

technique.

22. Method according to claim 21, characterised in that said at least one either deterministic and stochastic numerical technique comprises an estimation through the Montecarlo method and/or an evolutionary type search algorithms, preferably a genetic algorithm.

23. Method according to any one of claims 18 to 22, characterised in that the device is a device according to claim 12.

24. Controller device (10, 20), characterised in that it is capable to operate as controlling electronic means mezzo of a single stage inverter device according to any one of claims 1 to 13.

25. Controller device (10, 20) according to claim 24, characterised in that it is capable to perform the single switching cycle method of controlling switching means according to any one of claims 14 to 17.

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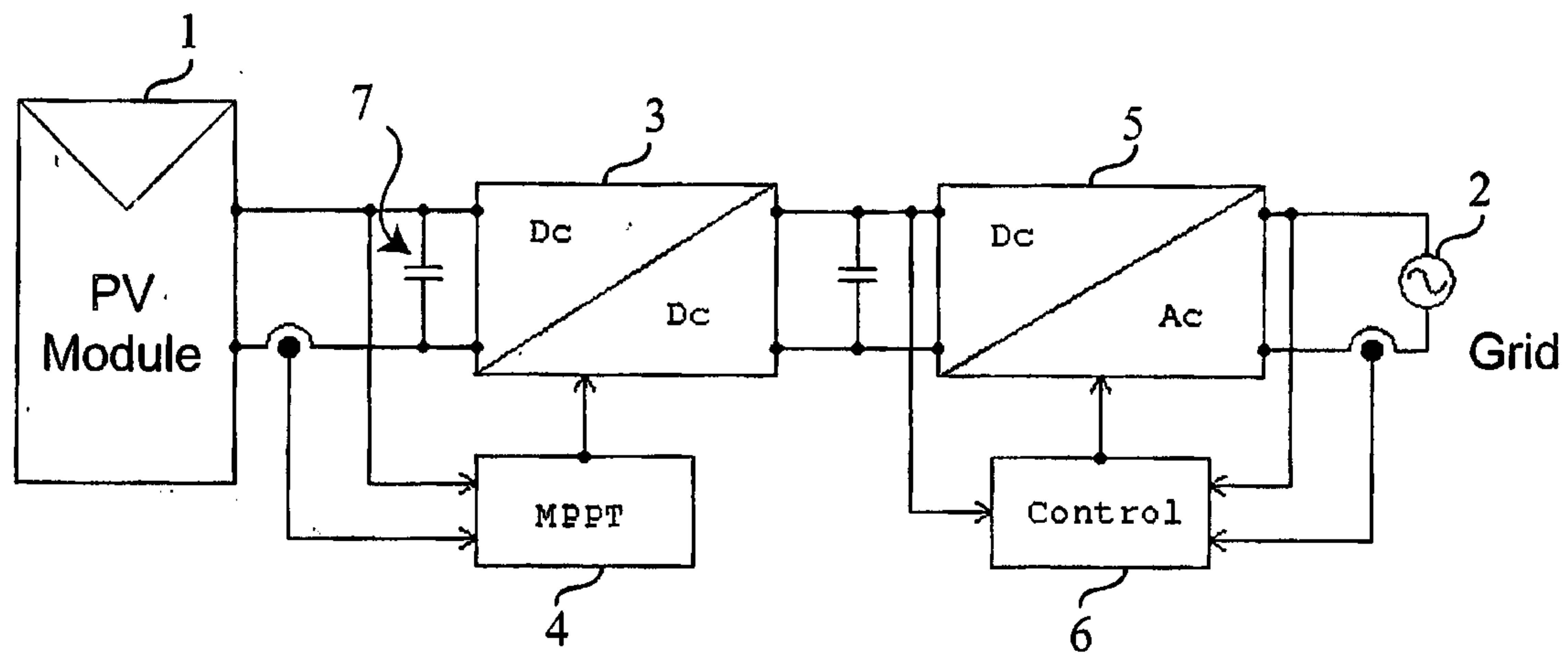


Fig. 1 PRIOR ART

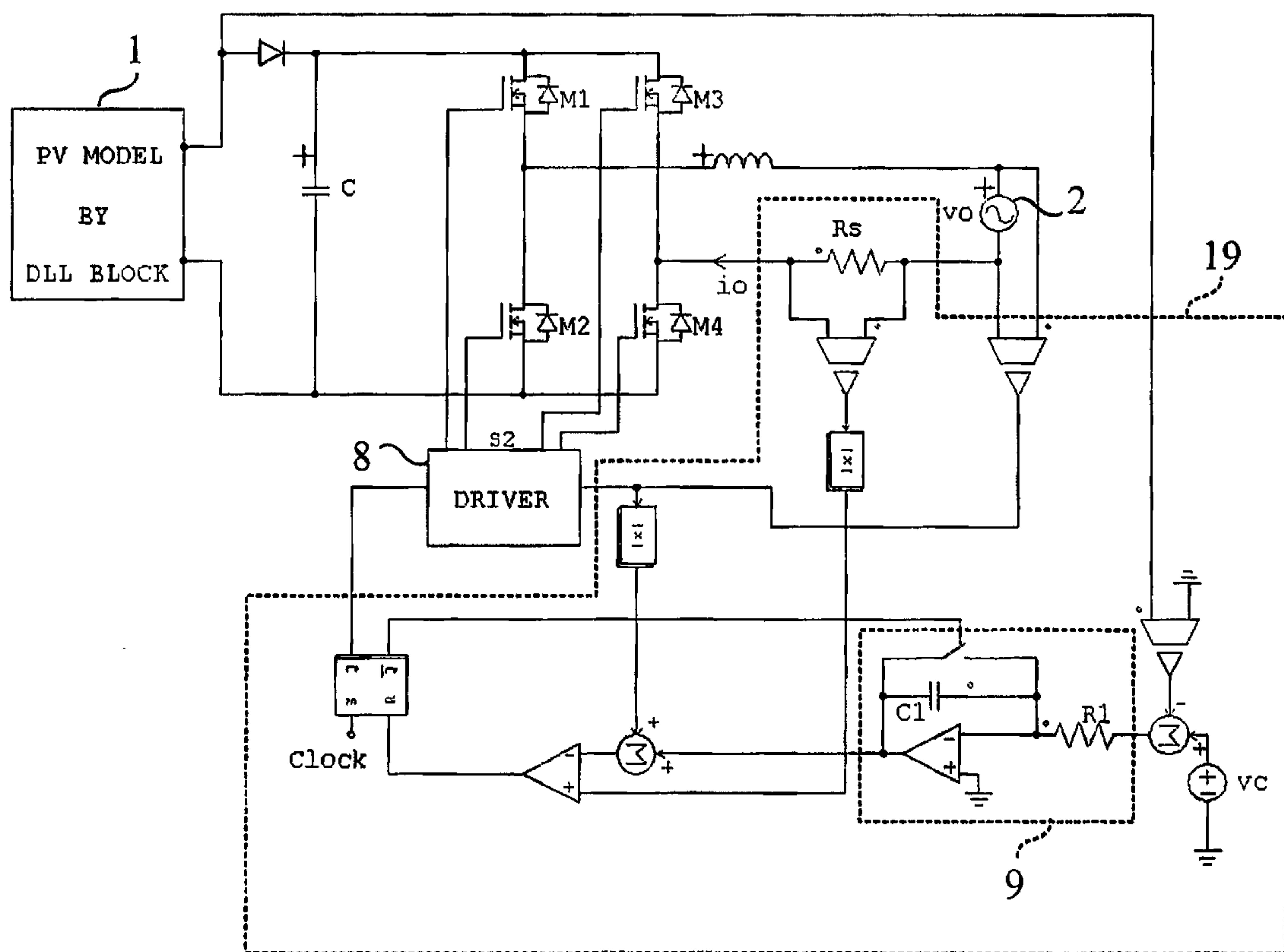


Fig. 2 PRIOR ART

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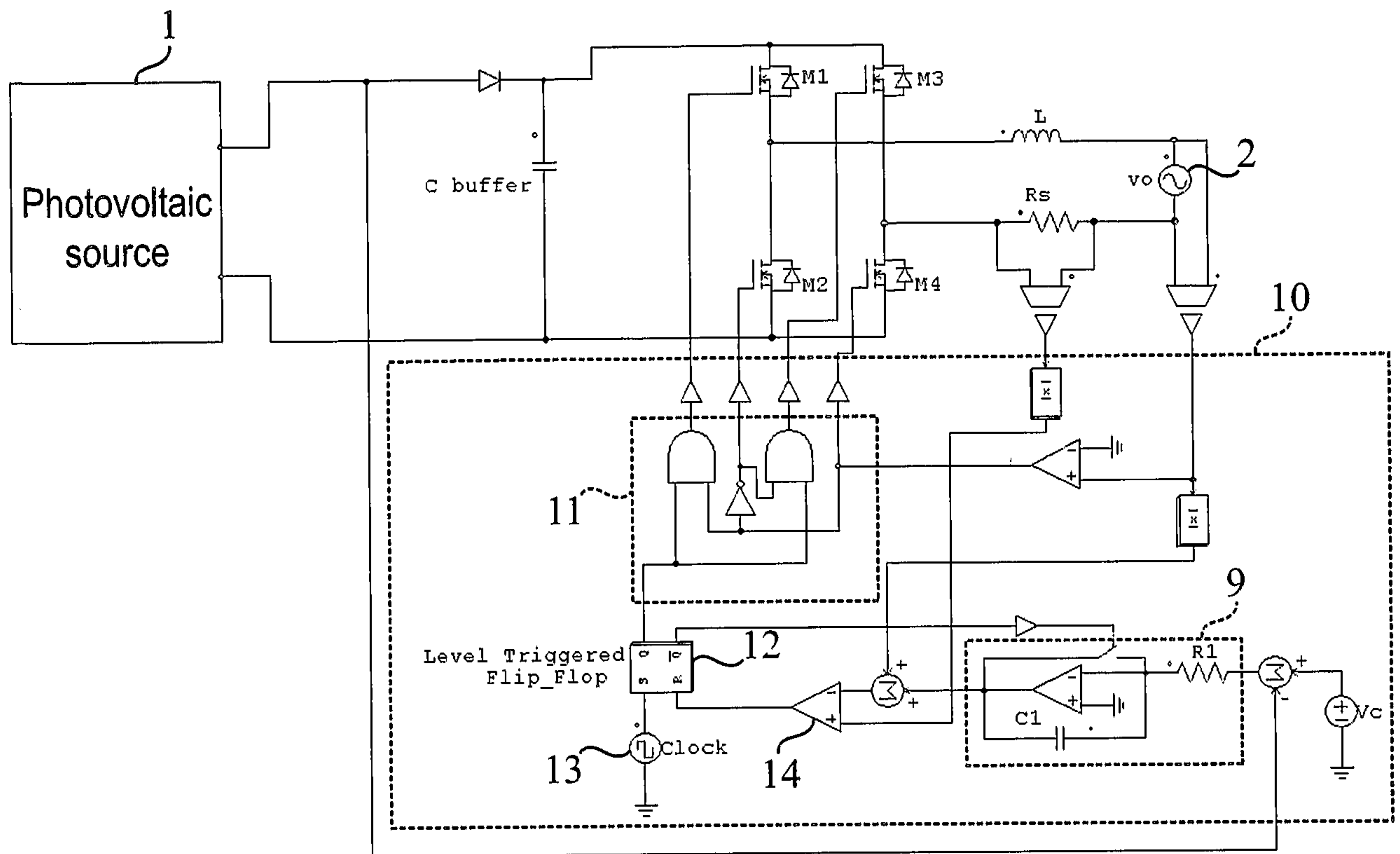


Fig. 3

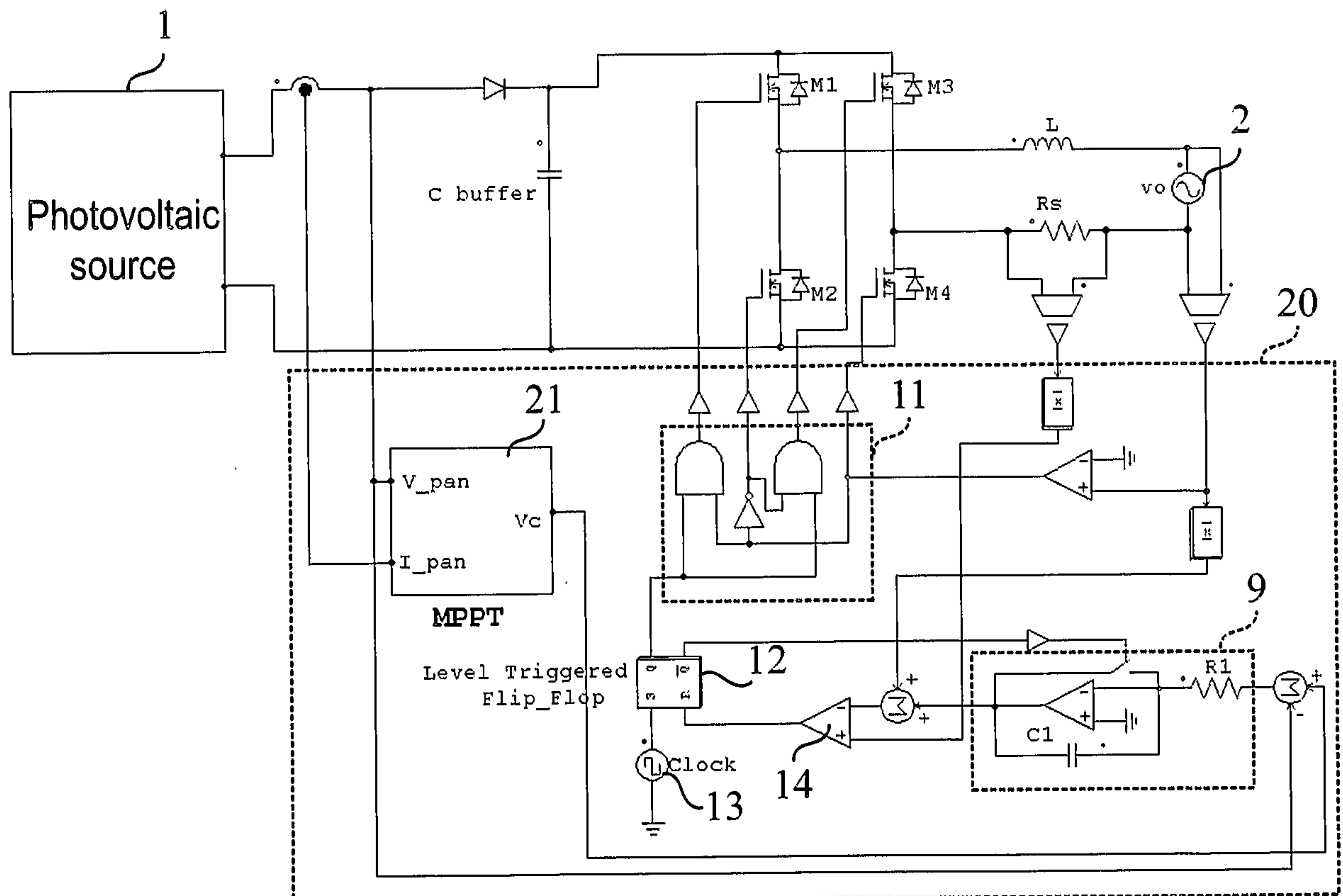


Fig. 18

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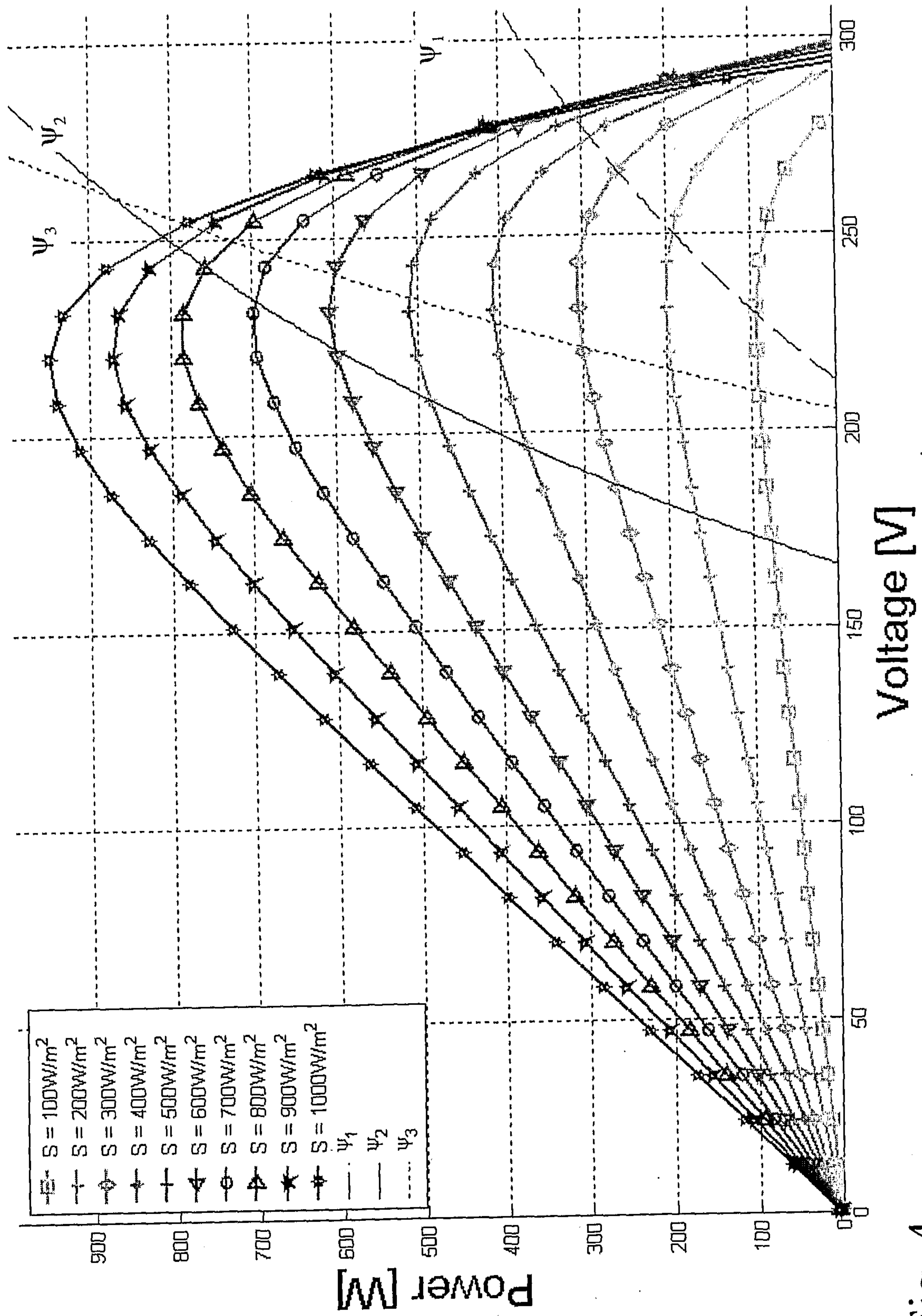


Fig. 4

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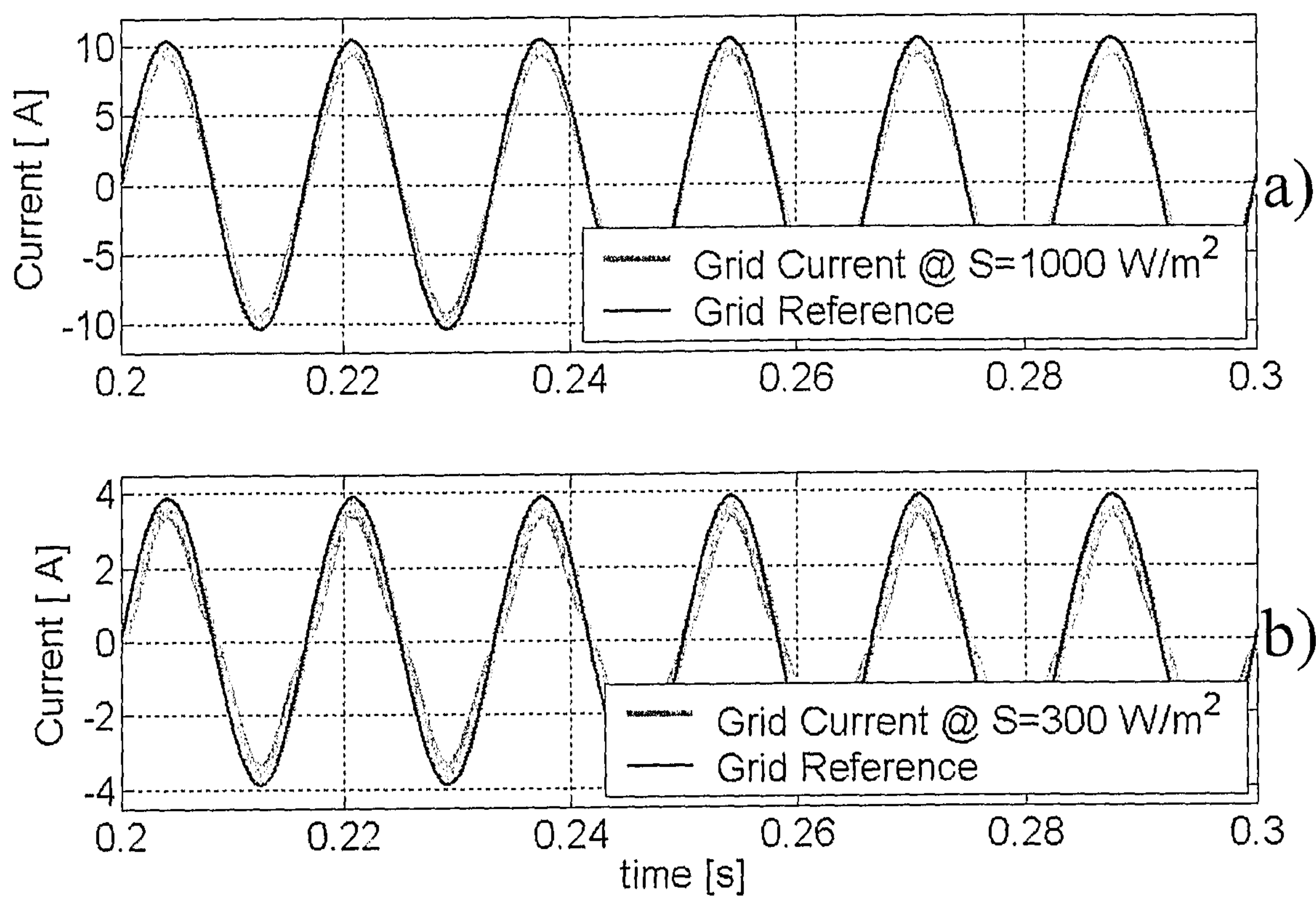


Fig. 5

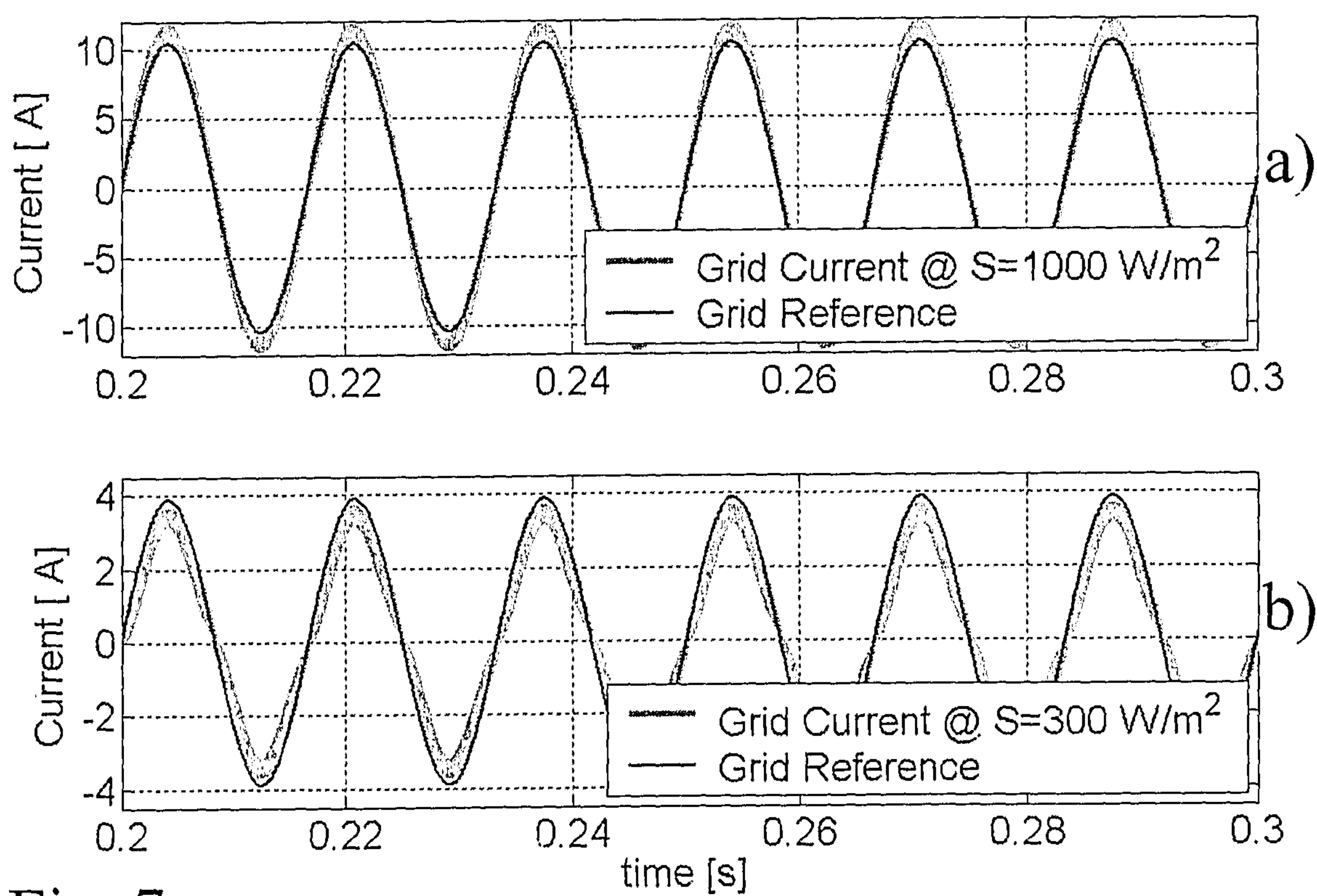


Fig. 7

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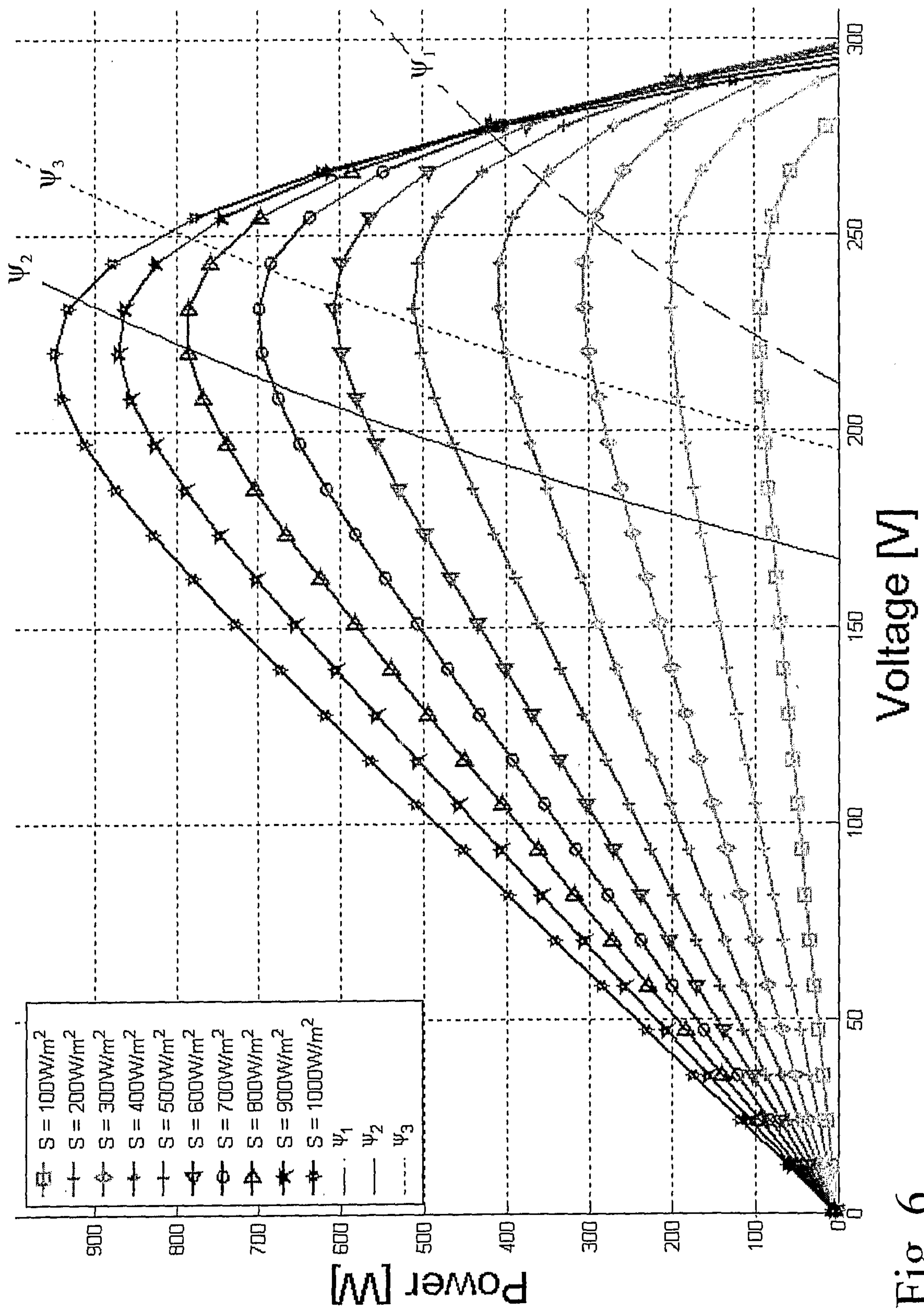


Fig. 6

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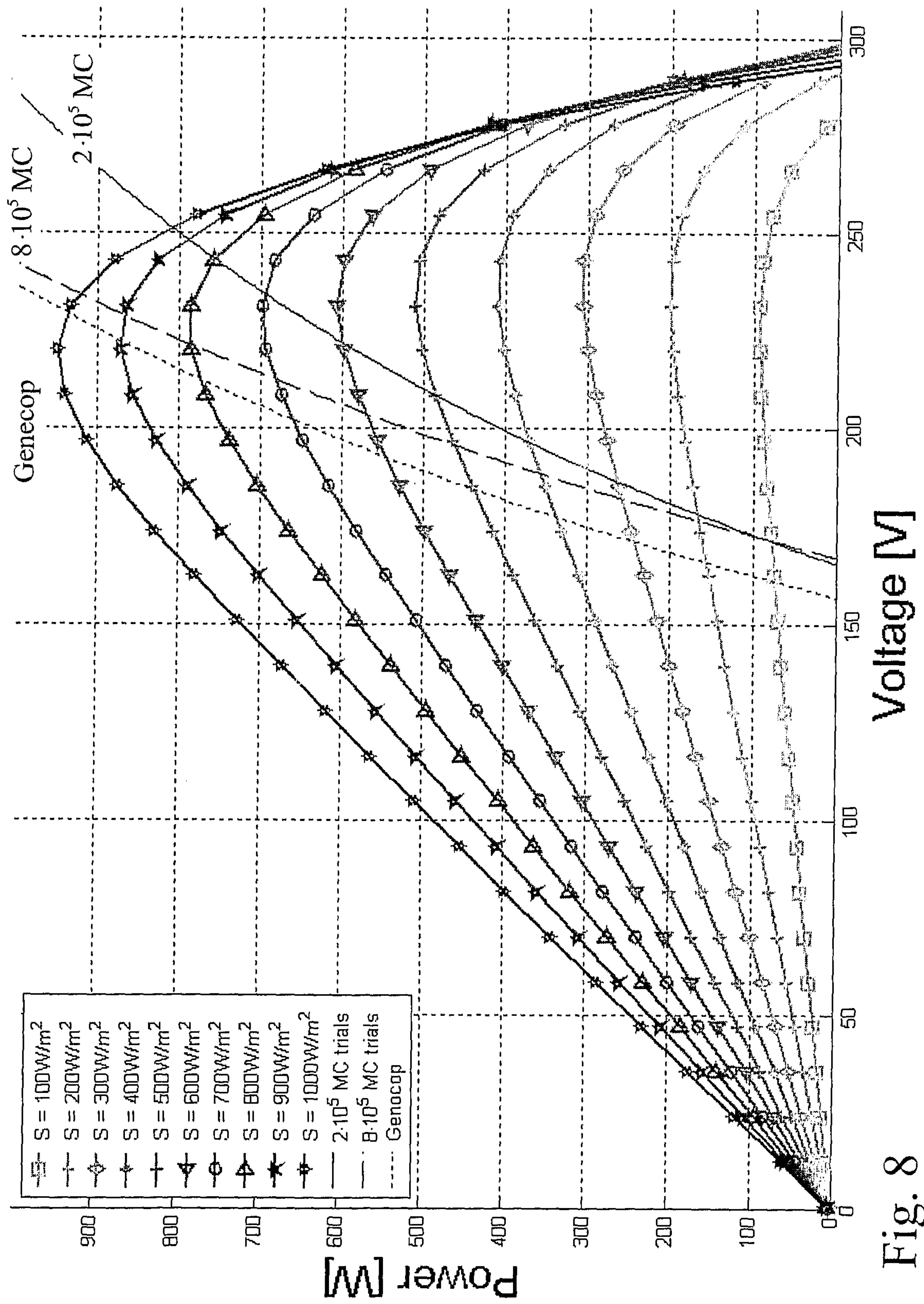


Fig. 8

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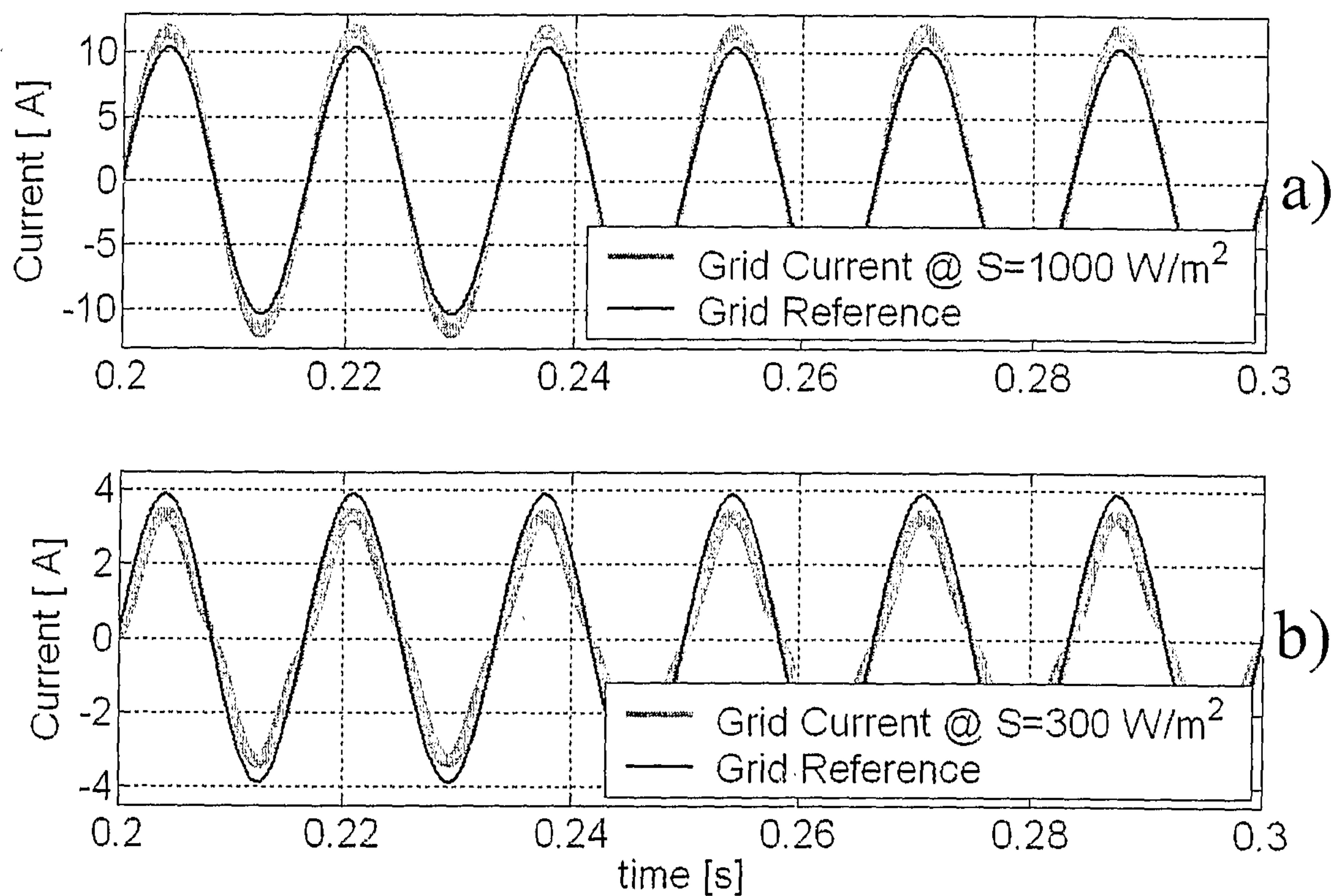


Fig. 9

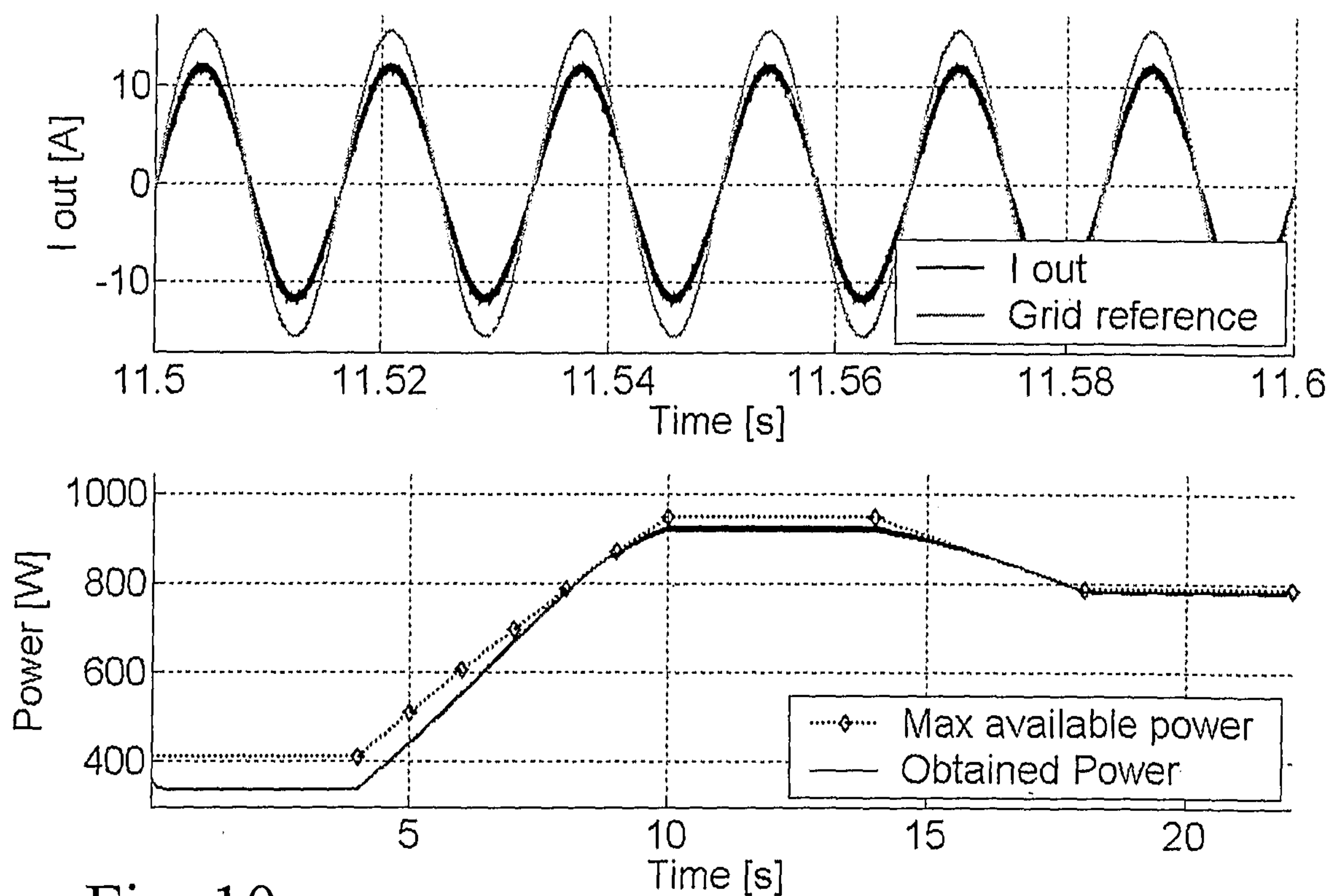


Fig. 10

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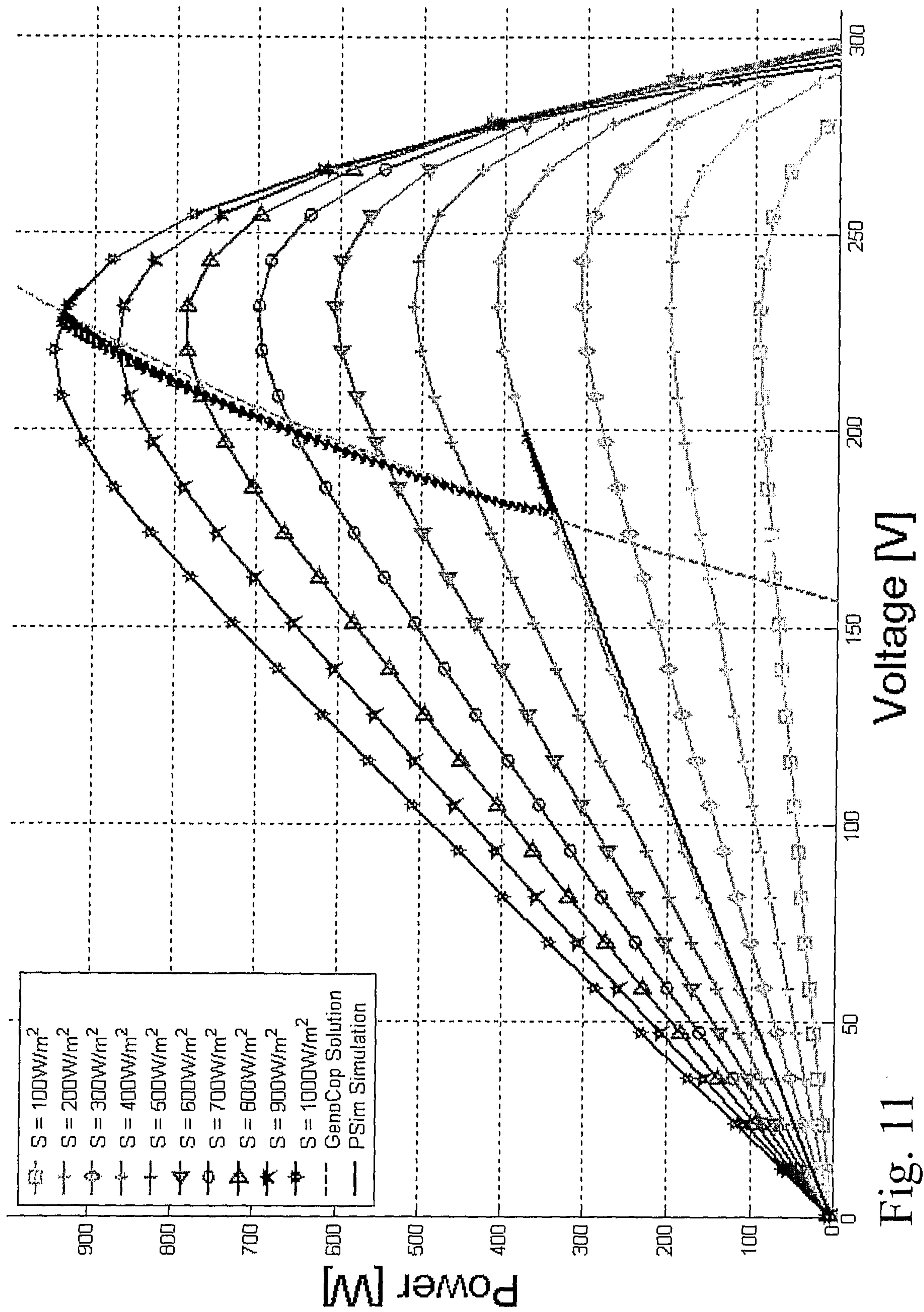


Fig. 11

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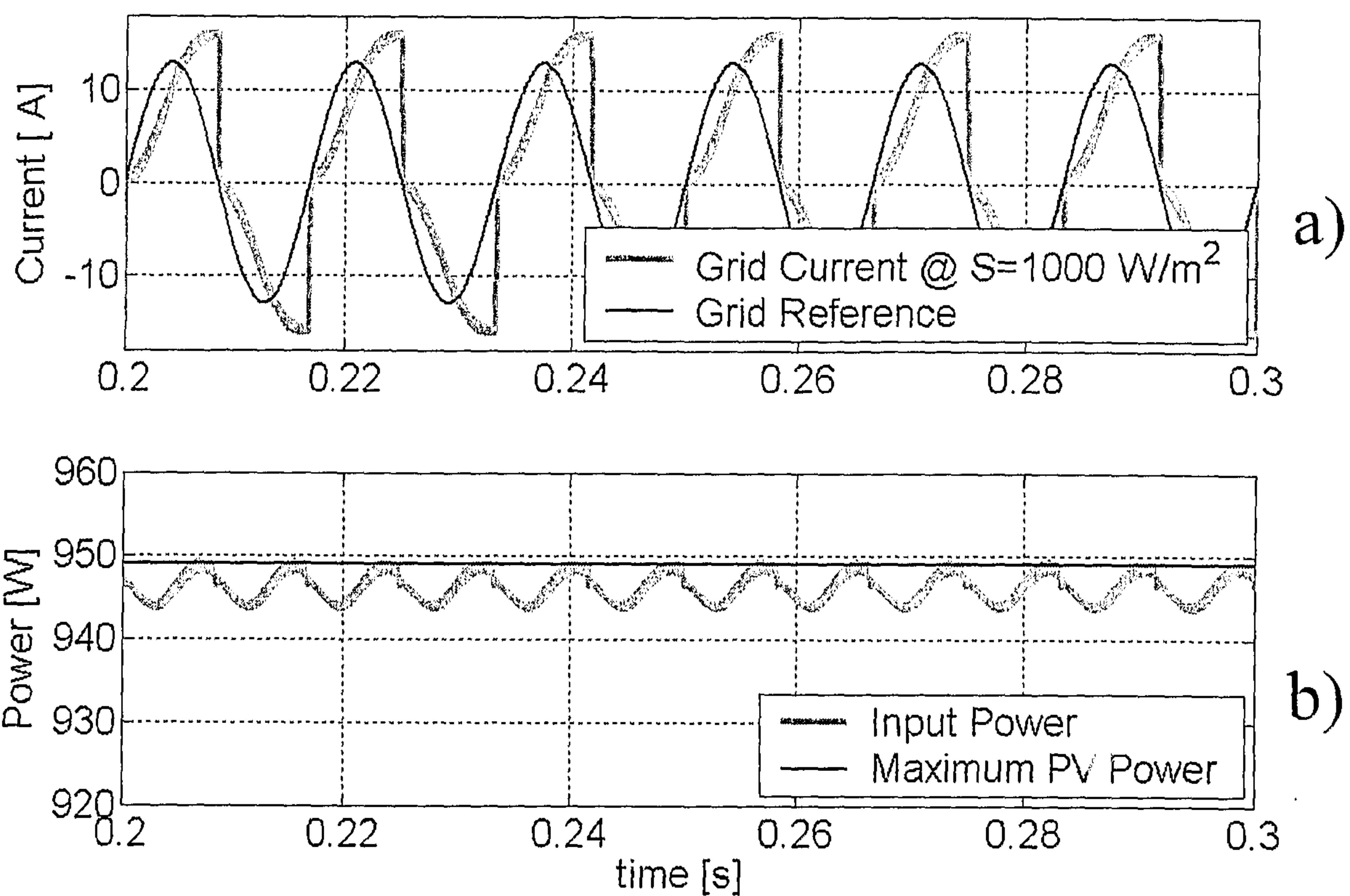


Fig. 12

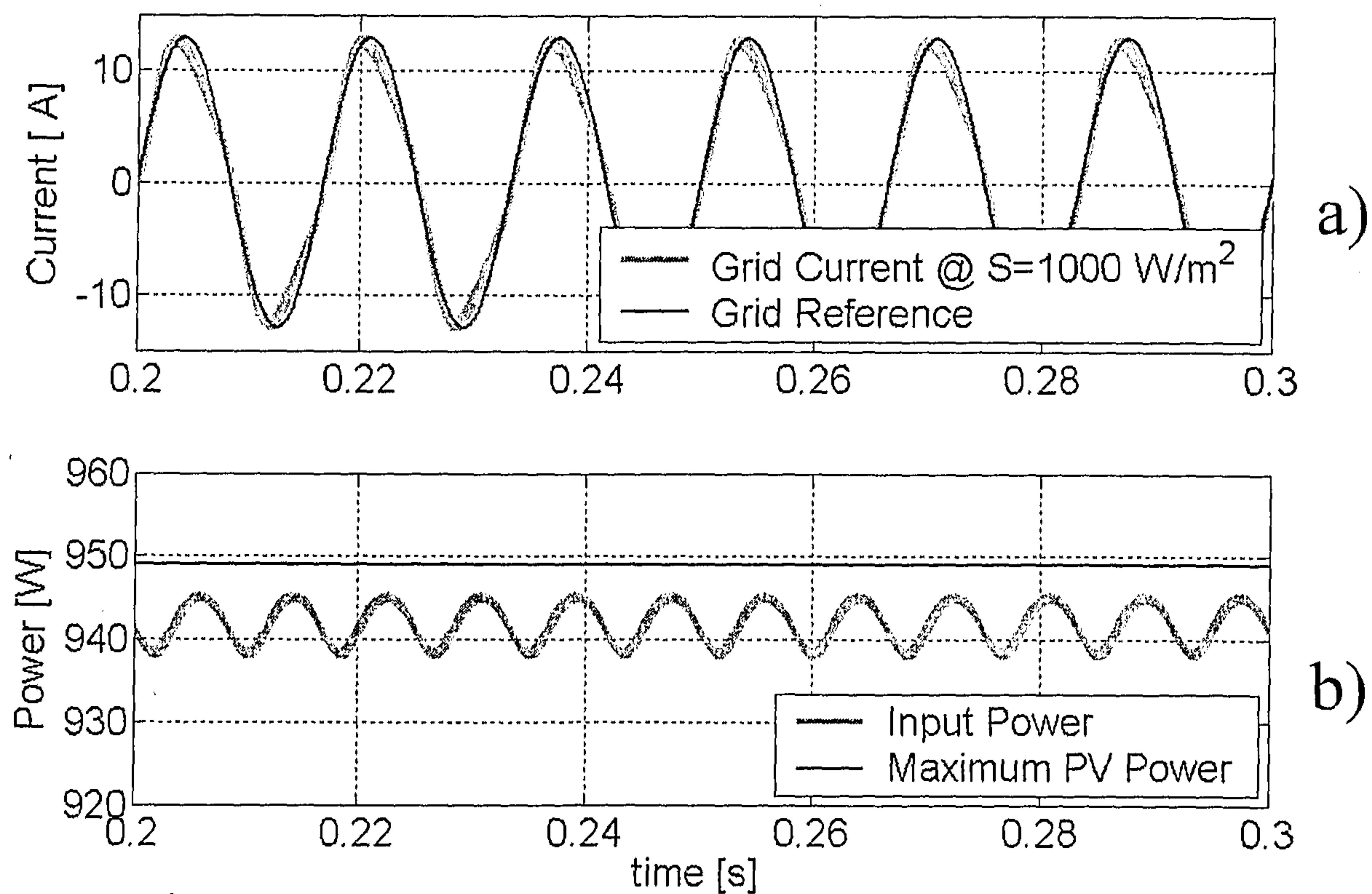


Fig. 13

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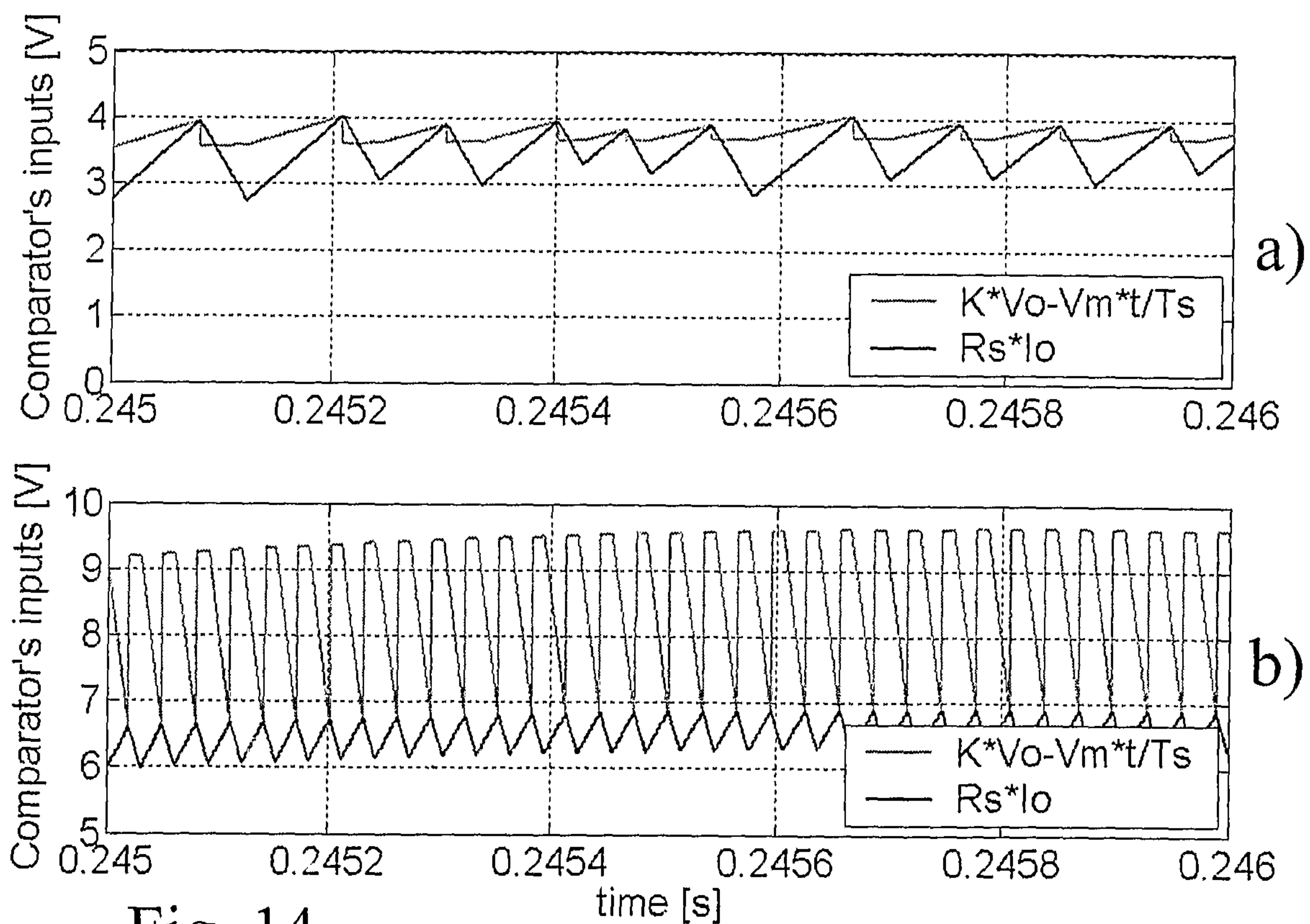


Fig. 14

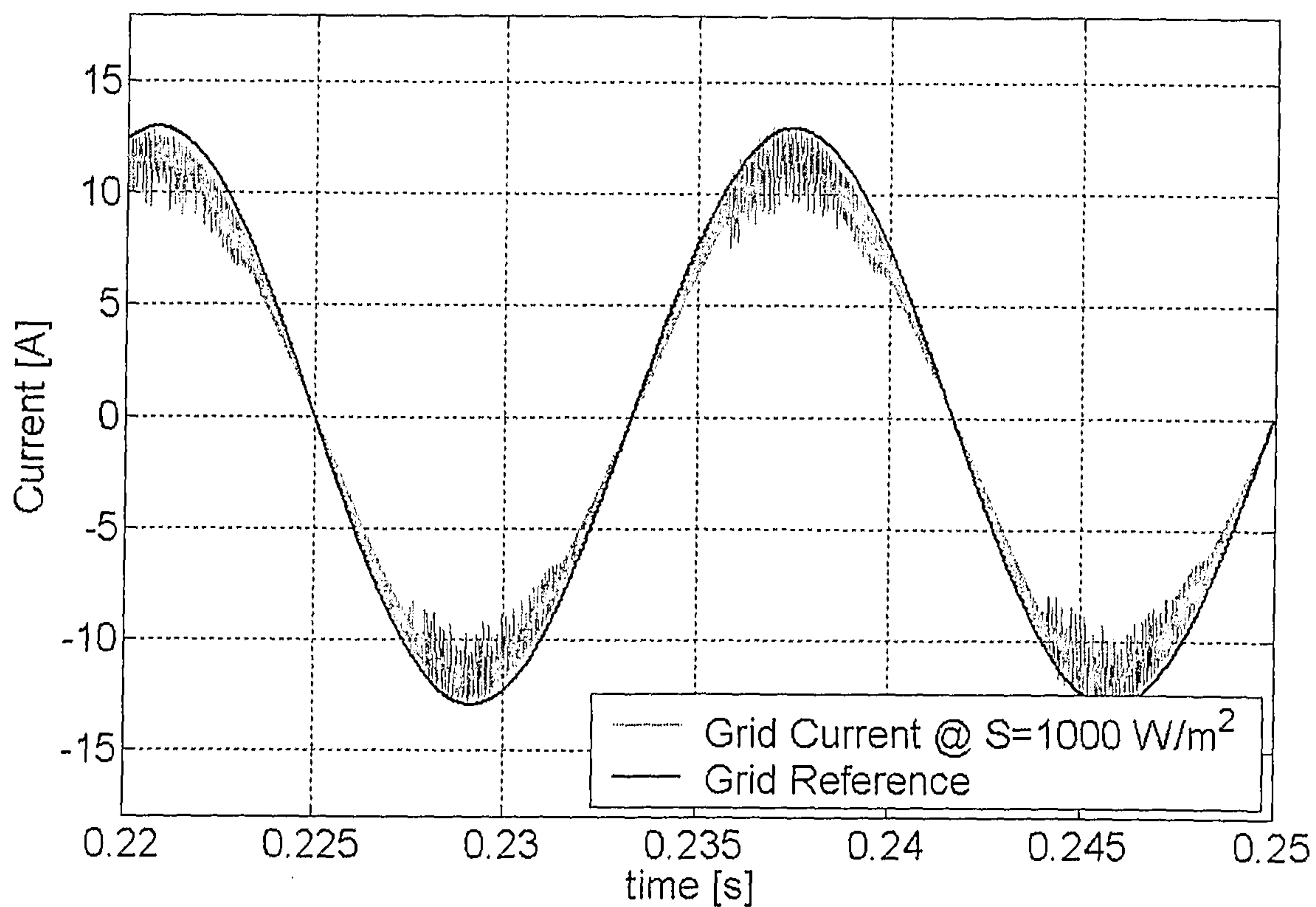


Fig. 15

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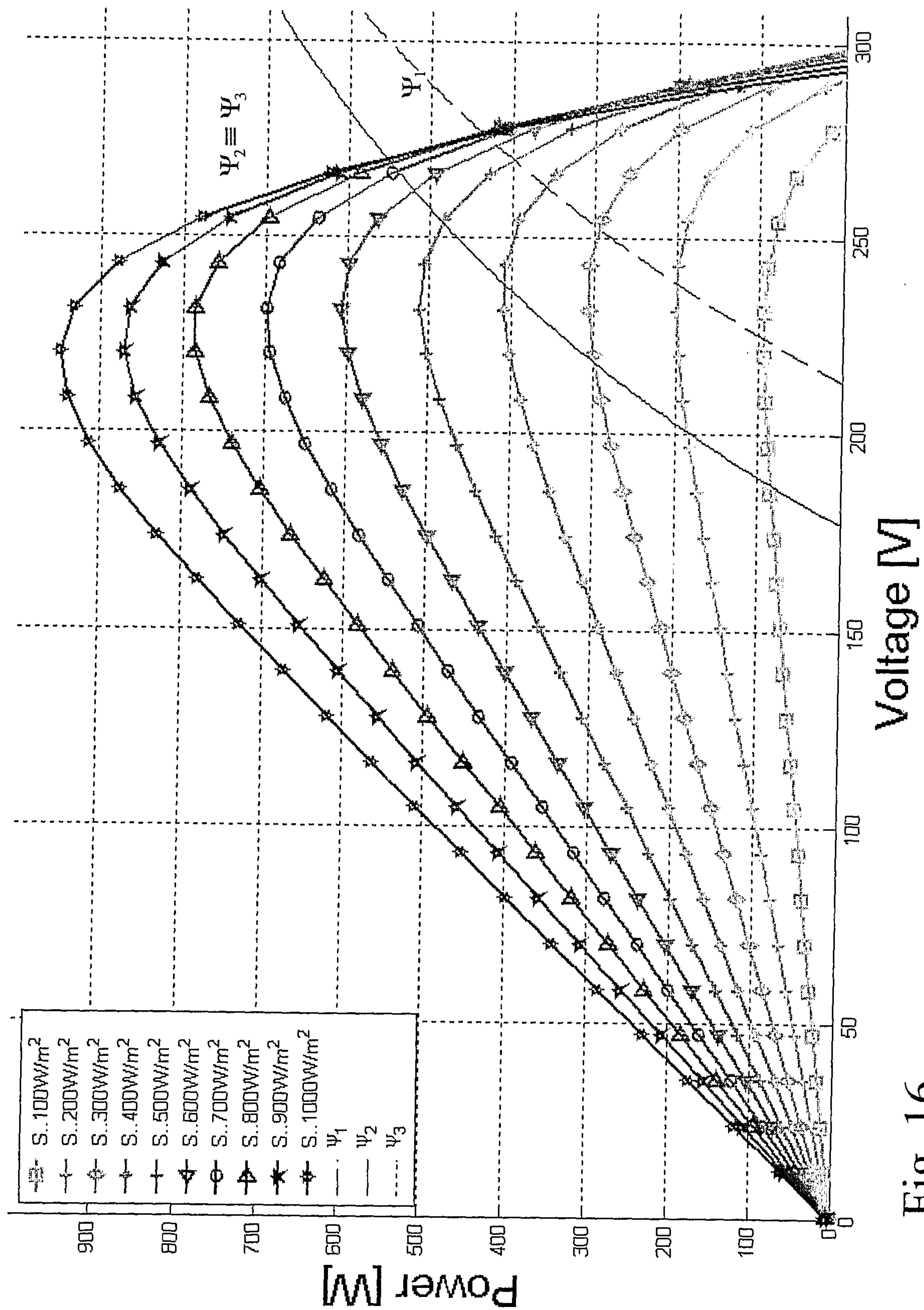


Fig. 16

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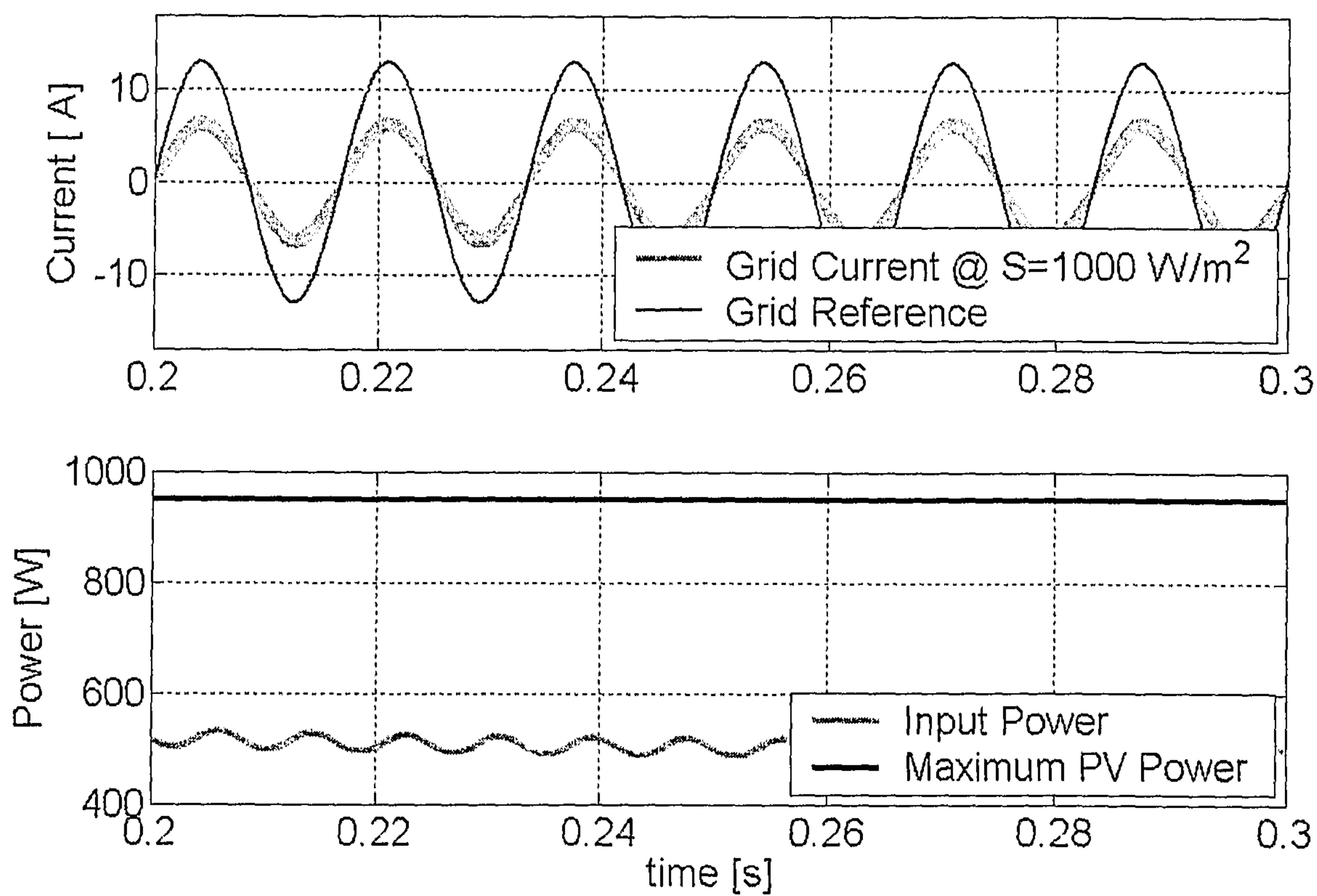


Fig. 17

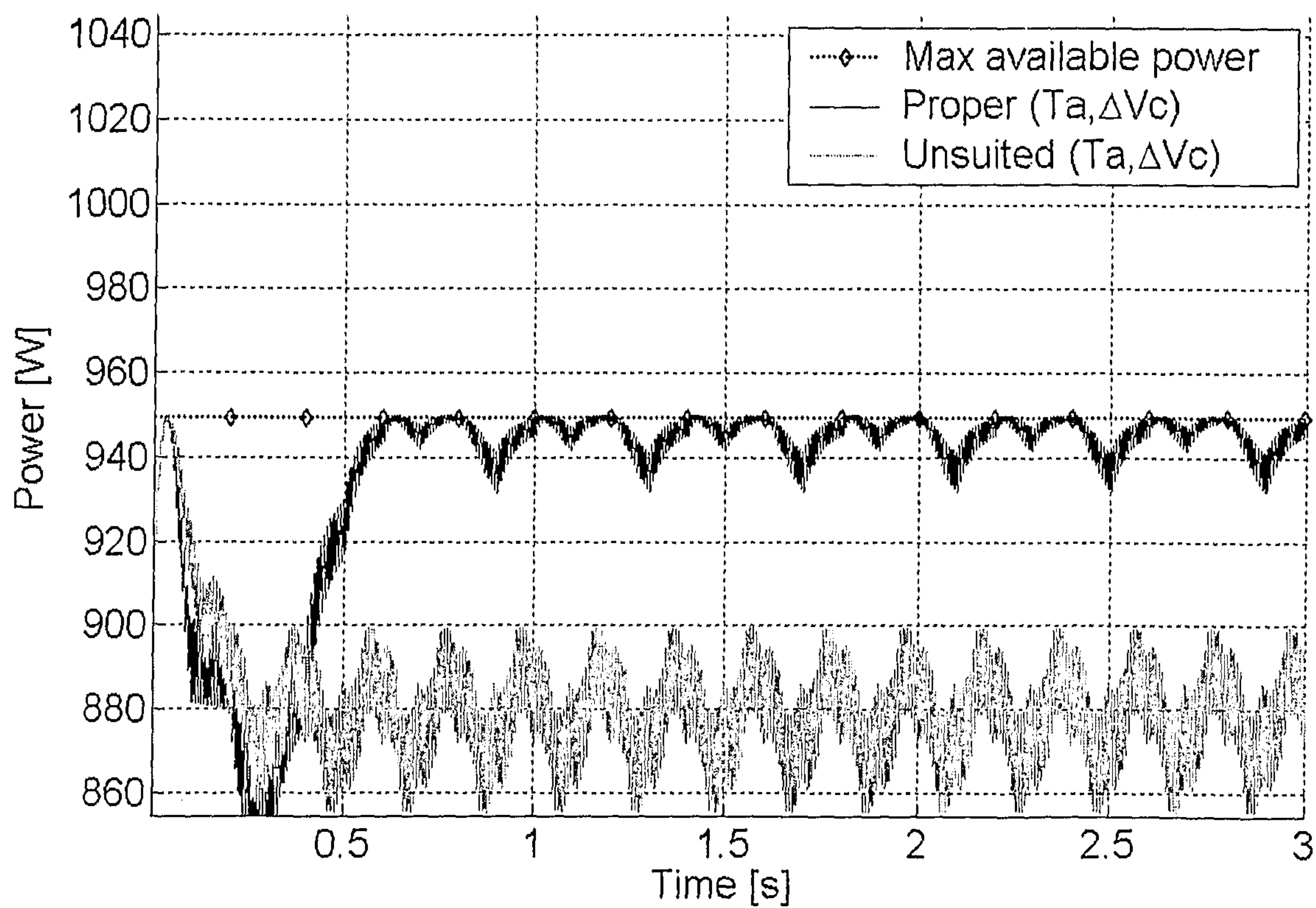


Fig. 20

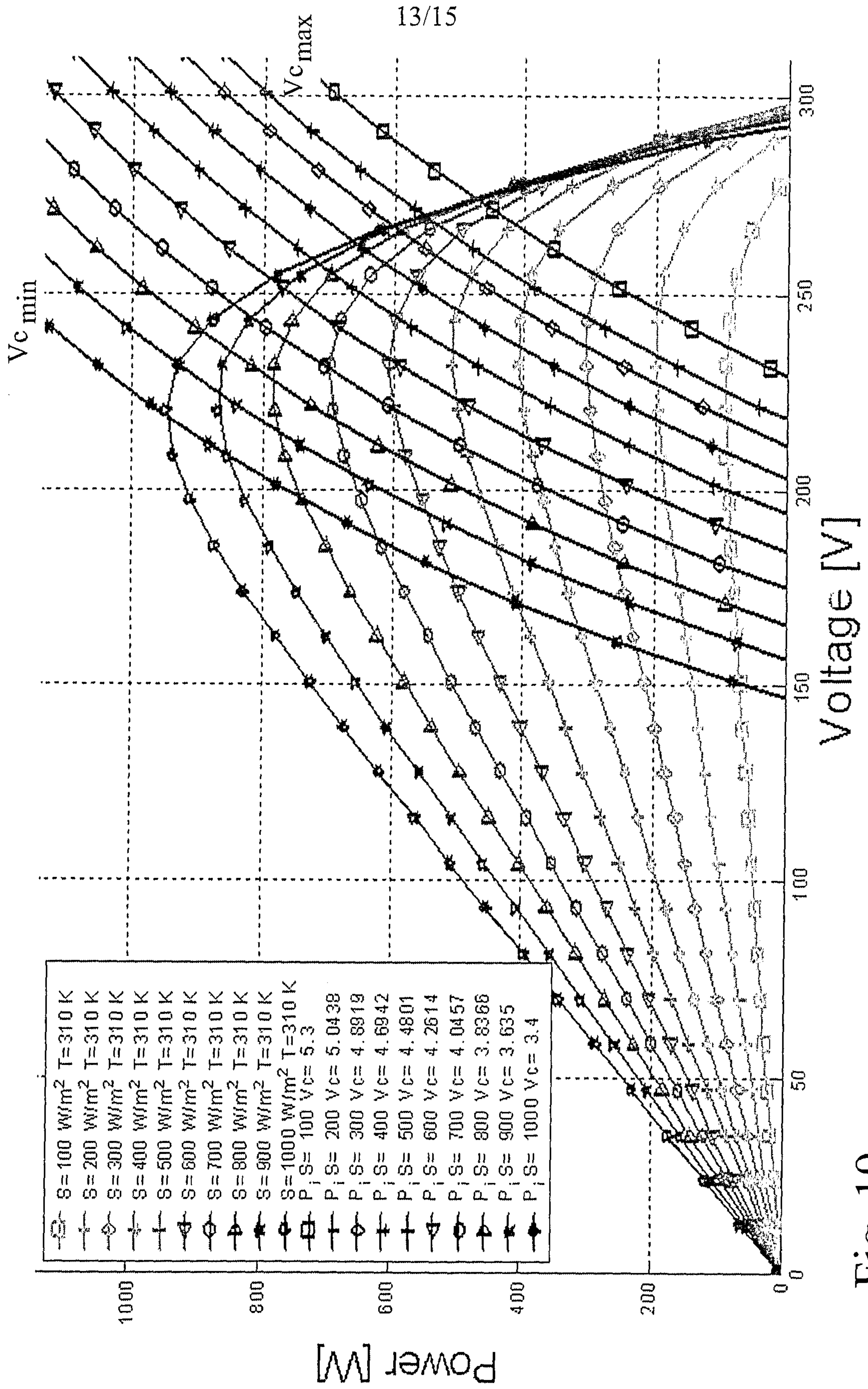


Fig. 19

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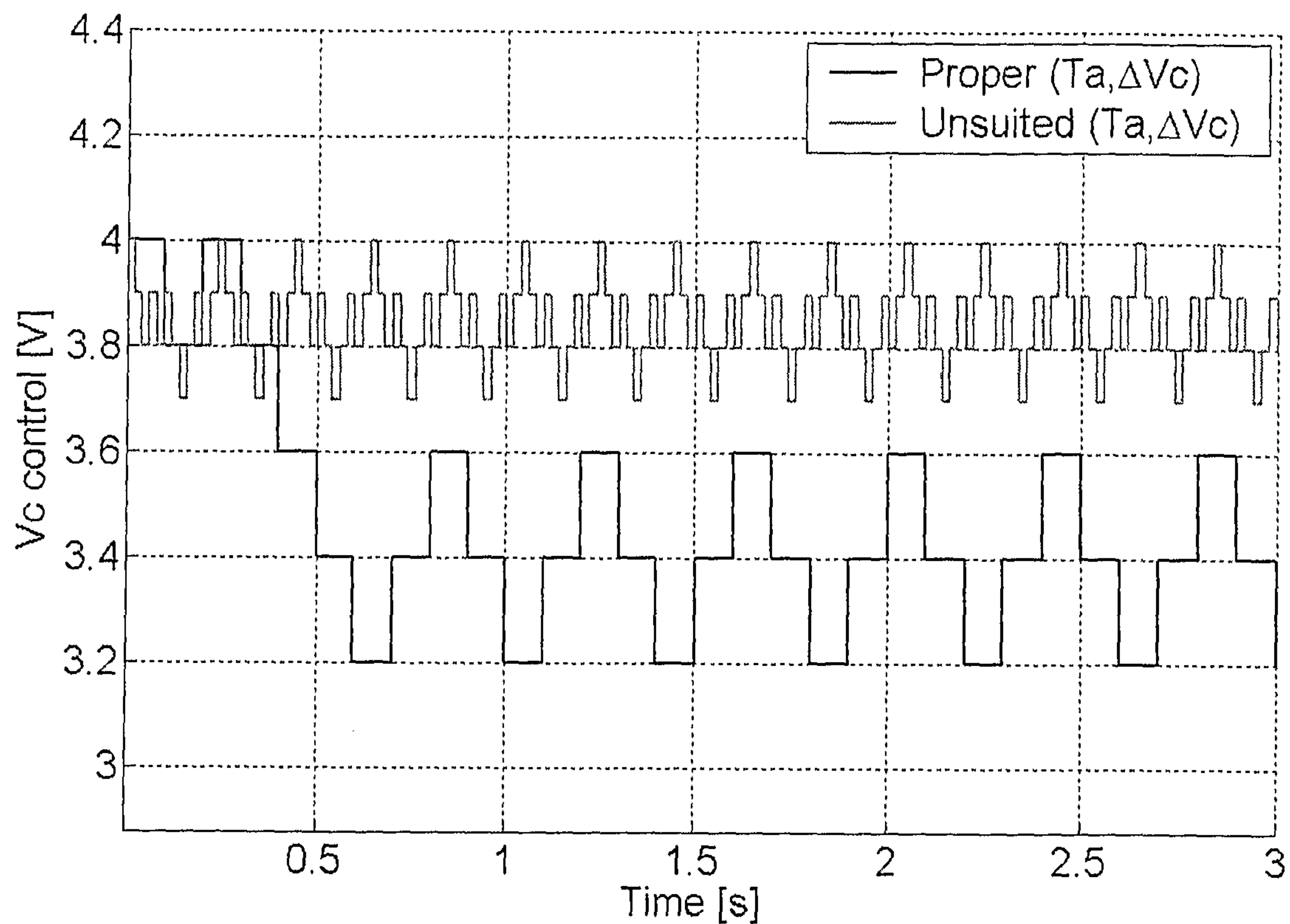


Fig. 21

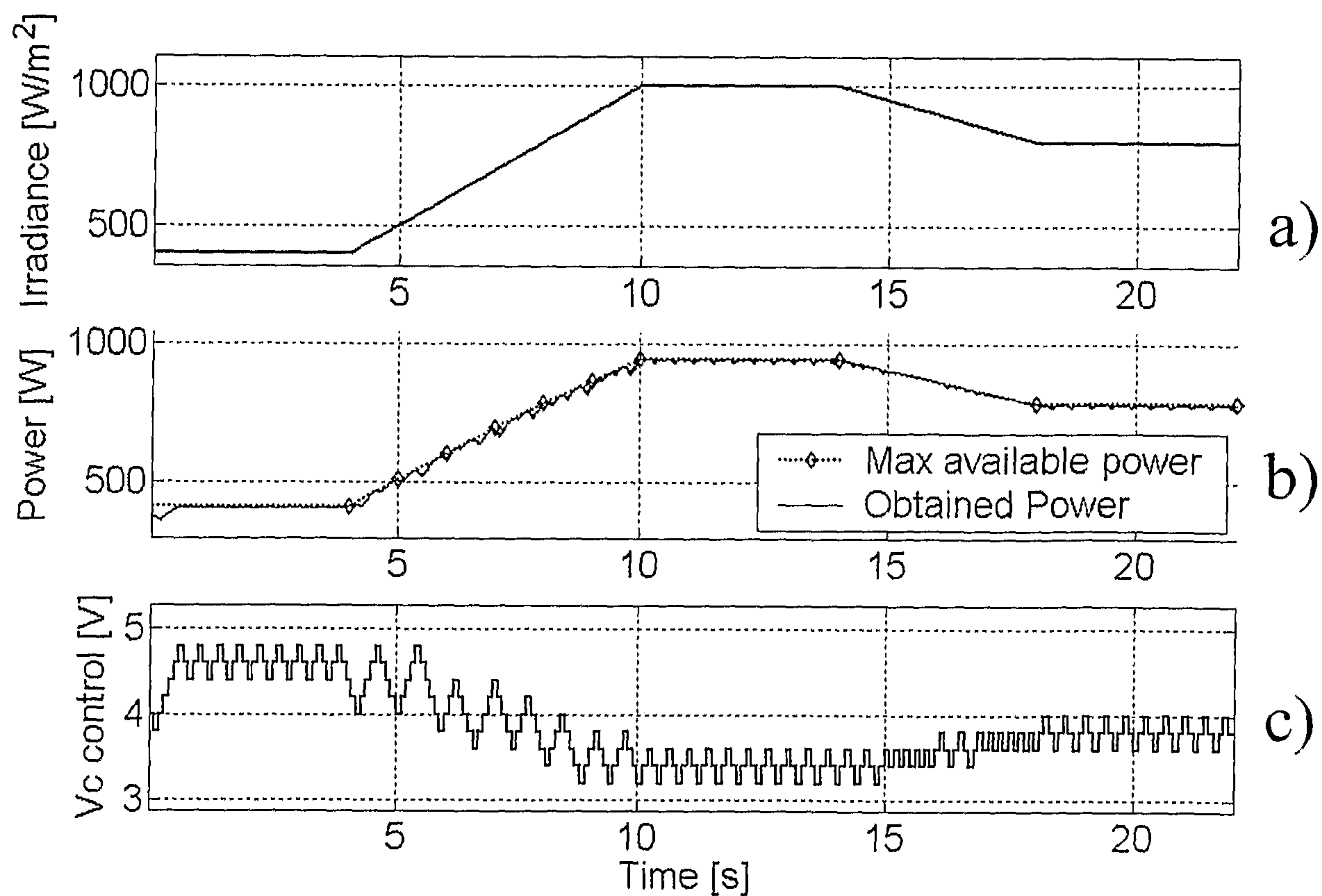


Fig. 22

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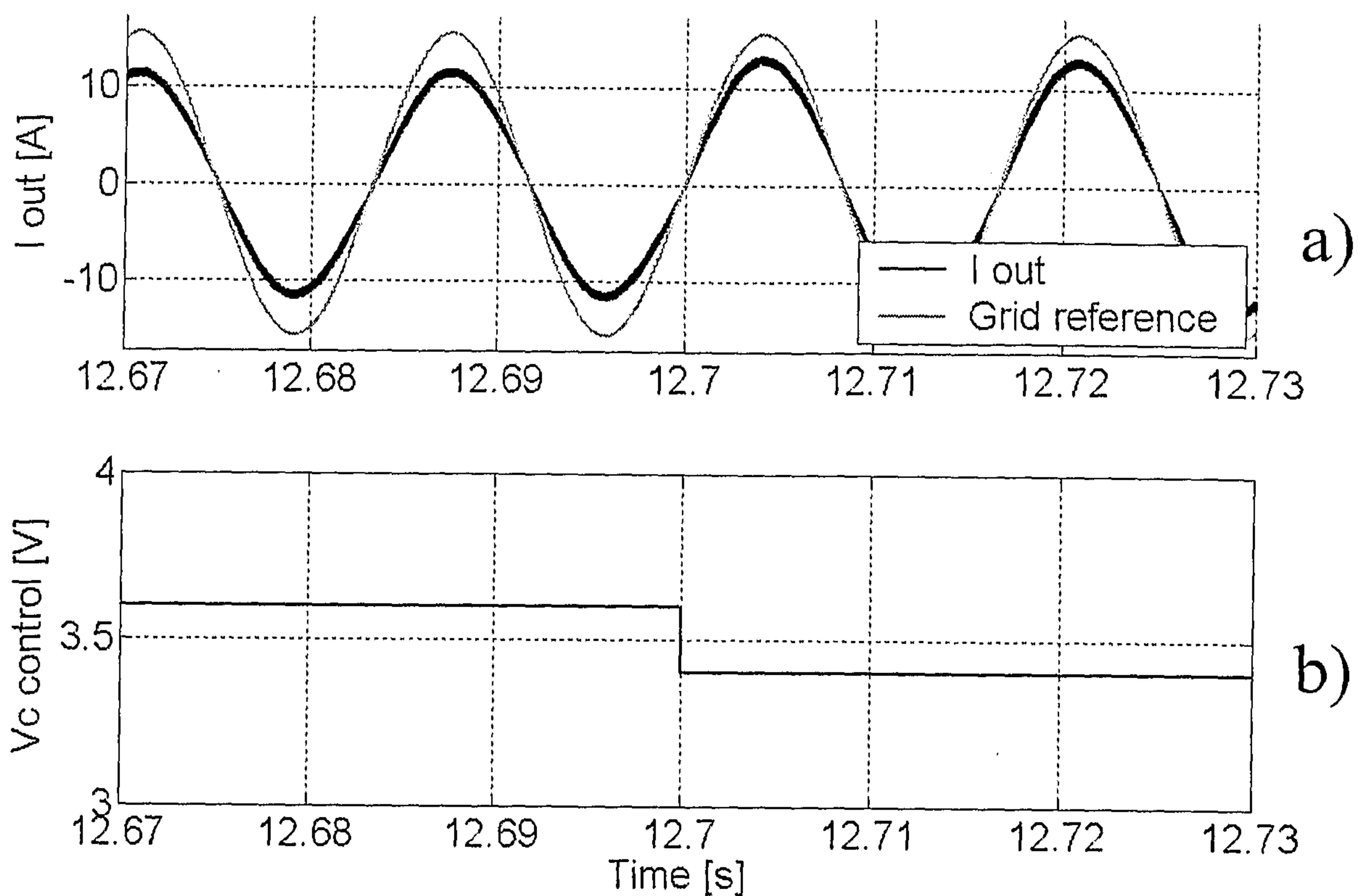


Fig. 23

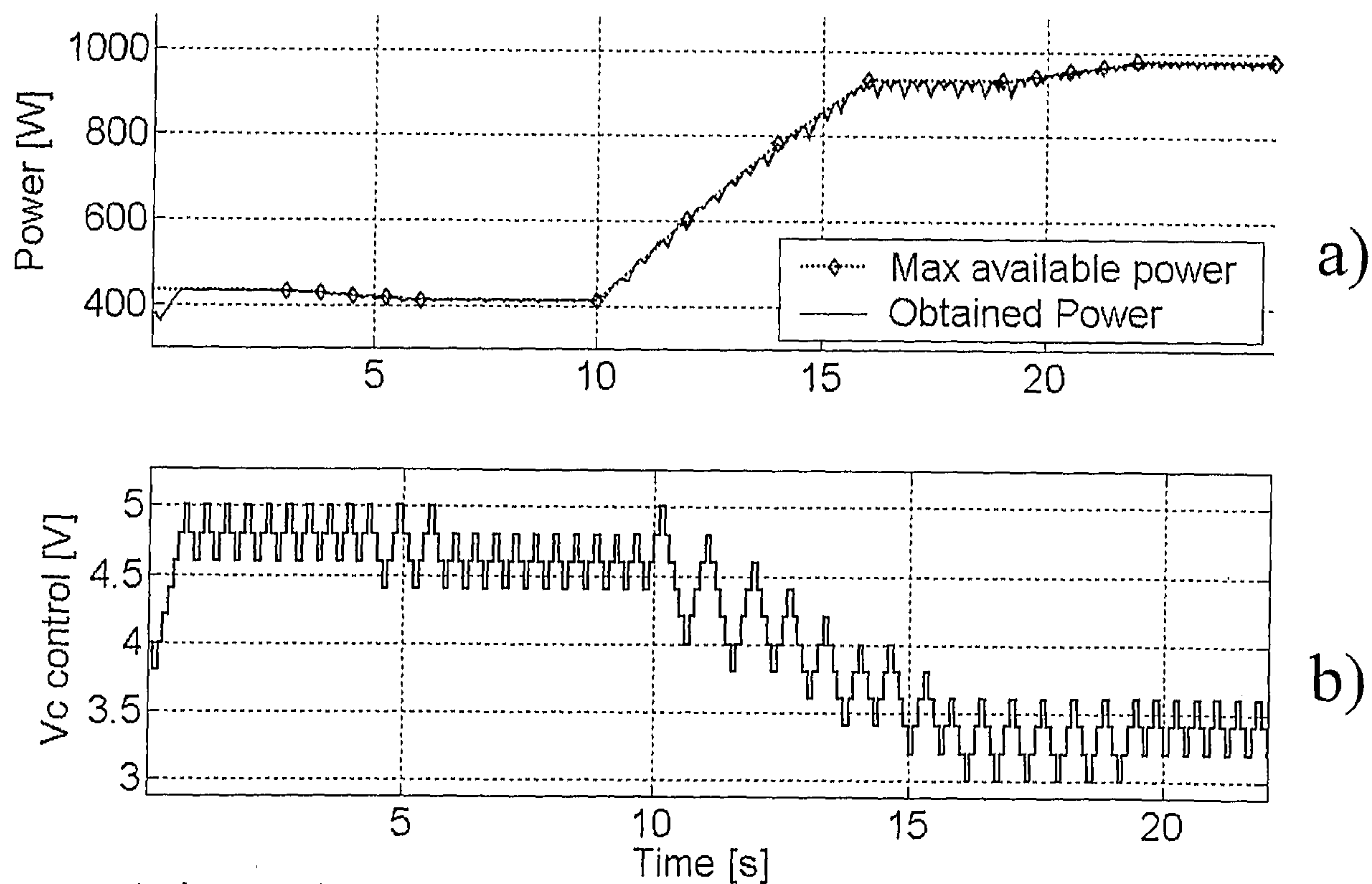


Fig. 24

