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Siemens-Reactor's High-Frequency Power Supply

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A detailed mathematical model is developed to calculate the radial temperature profile in silicon rods by heating currents of different forms. The model is based on the heat and Maxwell equations and on an expansion in Fourier series. Sinusoidal, pulsed unipolar and bipolar-like currents and their combinations as well were adopted to investigate the effect. Mathematical models and laboratory devices have been built to implement high-frequency power supply (frequency higher than 50 kHz). The power supply is a resonant inverter with two cells (sub-modules) that contains new technology with modern IGBT-transistors, low induction capacitors and toroidal core from amorphous nanocrystalline alloys. New high frequency transport technology with twisted-pair cable has been used to decrease reactive and active loss power.

1. Introduction

One of the key issues for the development a modern society is sustainable development and renewable energies including the photovoltaic sources (Tiepoloa et al., 2013). On one side, sustainable development and the reduction of greenhouse gas emissions are matters of great concern in process development and design (Sha et al., 2013). On the other, side PV industry experiencing a deep crisis at the moment. Despite it, the research has been conducted in order to reduce production costs and increase the future polysilicon market competition for polysilicon plants reconstruction and transformation. Analysis of energy consumption in main plants of polysilicon by Ke et al. (2013) shown that multi-effect distillation, reducing heat energy comprehensive utilisation system, and cold hydrogenation process can save energy and reduce polysilicon cost greatly. Huang and Liu (2013) was developed a novel Chemical Vapour Deposition (CVD) reactor. The energy consumption of the novel reactor was < 8% than that of the traditional reactor by simulation results. It is well known that Siemens technology, based on CVD, is the most widespread process for the production of high-purity polycrystalline silicon. It consists of batch reactors where a set of polysilicon rods are heated by intensively supplying electrical energy and they are progressively increased in volume (Ceccaroli, 2003). The main limitation of this technology is related to the relevant internal temperature gradient within the silicon rods due to the poor conductivity of silicon and the growing diameter as well. The fact that the electrical conductivity of pure silicon increases with increasing temperature (Fan et al., 2008) leads to a greater increase of the current density flowing in the centre of the rod (Mitrasinovic et al., 2009) and thereby this region becomes hotter (del Coso et al., 2007). Such a temperature gradient induces mechanicals stresses and limits the possibility to obtain large rods without melting the core of the rod, with consequent losses of the polycrystalline nature of silicon inside the rod (Hou et al., 2013). An effective way to overcome this limitation, without the inclusion of design changes in the Siemens-reactor, is the use of high-frequency current sources (Dawson et al., 2003). In this case, the temperature profile within the rod is smoother because most of the current density migrates to the rod's outer region (the so-called skin effect). The result is a high overall deposition rate of silicon, with optimum temperature deposition, and a minimized breakdown risk; this allows reducing the process time, thus reducing energy costs and technological expenses.

The state-of-the-art provides one invention of high-frequency current sources, which addresses the relevant internal temperature gradient problem inside silicon rods, proposed by company "AEG Power

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Solutions" (Wallmeier, 2009). This power supply is implementing AC as a superposition of two harmonics with a carrier frequency of 50-60 Hz.
In this context, the aim of this work is the development of a new resistive heating method for silicon rods, which ensures the reduction of the internal temperature gradient, and its practical implementation to test different power supplies.

2. Mathematical model of the radial temperature profile

The temperature profile inside the silicon rod is influenced by two key factors: the distributed nature of the sources of internal heating by Joule effect and the heat transfer with the environment. The mathematical model of the radial-dependent temperature distribution $T(r)$ uses an approach proposed by del Coso (2007). The model uses the differential equation of stationary heat conduction in a cylindrical coordinate system with a radially distributed heat source:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\cdot\lambda(T)\cdot\frac{\partial T}{\partial r}\right)+\sigma(T)\cdot\left|E(r)\right|^{2}=0\,, \tag{1}$$

with boundary equations:

$$\begin{aligned}&\left.\frac{\partial T}{\partial r}\right|_{r=0}=0,\\&-\lambda(T)\cdot\frac{\partial T}{\partial r}=k_{con}\left(T-T_{g}\right)+\varepsilon_{\mathrm{Si}}\sigma_{B}\left(T^{4}-T_{w}^{4}\right)\ on\ r=R,\end{aligned} \tag{2}$$

where r – radial coordinate, mm; λ – silicon thermal conductivity, W/(m·K); σ – silicon specific conductivity, S/m; E – electric field, V/m; R – rod radius, m; T_g – gas temperature, K; k_{con} – convection coefficient, W/(K·m^2); σ_B – Stephan-Boltzmann constant, W/(K^4·m^2); $\varepsilon_{\mathrm{Si}}$ – silicon emissivity; T_w – reactor's wall temperature, K.
Maxwell equation leads to the Helmholtz equation since the problem is symmetric, thus the differential equation related to the electric field $E(r)=J(r)/\sigma(T)$ for a current of sinusoidal form may be obtained:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right)+k(T,\omega)\cdot E=0 \tag{3}$$

with boundary conditions:

$$\left.\frac{\partial E}{\partial r}\right|_{r=0}=0\quad, \tag{4}$$

$$I_{tot}=\int\limits_{S_{rod}}\sigma(T)\,E(r)dS, \tag{5}$$

where ω – current angular frequency, rad/s; $k(T,\omega)=-j\mu\omega\sigma(T)$; μ – silicon magnetic permeability, H/m; S_{rod} – cross-sectional area of the rod, m^2; I_{tot} – RMS current, A; $J(r)$ – current density, A/m^2.
However, Eq(5) cannot be easily used for a numerical simulation. Using Eq(3), Eq(4) can be written in the following simple form of boundary condition:

$$\left.\frac{\partial E}{\partial r}\right|_{r=R}=I_{tot}\frac{j\mu\omega}{2\pi R}\,. \tag{6}$$

Sinusoidal, pulsed unipolar and bipolar-like currents and their combinations, proposed in Wallmeier (2009), were adopted to investigate the skin effect in polysilicon rod. The electric field E for a non-sinusoidal current was computed through the superposition method applied to electric fields, generated by harmonic currents derived from a Fourier-series expansion of the original current. The required number of terms in the Fourier-series expansion was determined by ensuring at least 99 % of the original RMS current. A set of conditions used for the simulations is given in Table 1. A general block diagram, relating to different current trends, that shows the algorithm employed for the evaluation of the radial temperature profile in the polysilicon rod is presented in Figure 1.

Table 1: Set of conditions used in the simulations of the radial temperature profile

Parameter	Value	Parameter	Value
Rod surface temp. T_s	1,423 K	Convection coefficient k_{con}	25 W/(K·m^2)
Gas temp. T_g	673 K	Silicon emissivity ε_{Si}	$-2.79\cdot10^{-4}\cdot T_s + 0.93$
Wall temp. T_w	373 K	Silicon thermal conductivity λ	$39{,}5\cdot e^{-T/62.7} + 108\cdot e^{-T/332.7}$ W/(m·K)
Magnetic permeability	$4\pi*10^{-7}$ H/m	Specific conductivity σ	$1.85\cdot10^{6}\ e^{-56300/(8.314\cdot T)}$ S/m

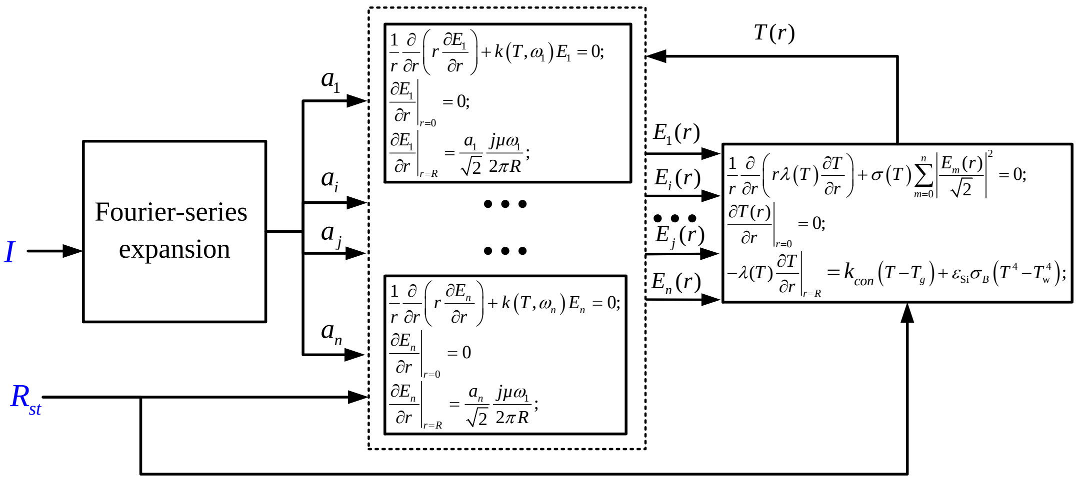

Figure 1: Polysilicon rod temperature profile evaluation block diagram

The temperature trends in the rod center and surface, achieved via simulation as a function of frequency, depending on the studied current shape, are given in Figure 2. Here the best results coming from the superposition of two harmonics with equal amplitudes, which can be implemented by the current source proposed by Wallmeier (2009), are shown. The mentioned current source has a low frequency component so the skin effect is small while the unipolar pulse current owns a DC component. As observed, the skin effect is best manifested in the resistive heating generated by harmonic or bipolar pulse current. Unlike the results of del Coso (2007) the skin effect is already evident at frequencies of 50 kHz (Figure 3).
The temperature gradient within the silicon rod as a function of frequency, for several diameters of the rod, is shown in Figure 4. As a result of the reported trends, it is convenient to develop source of bipolar currents with frequencies above 50 kHz.

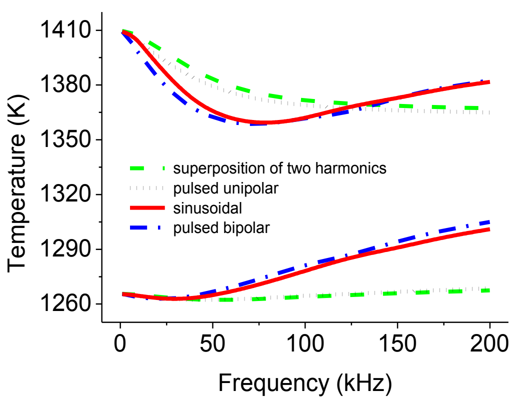

Figure 2: Temperature trend in the rod center and surface as a function of frequency (R = 75 mm)

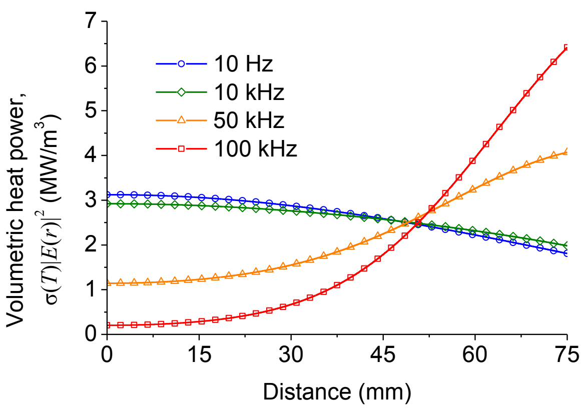

Figure 3: Volumetric heat power distribution in the silicon rod with its resistive heating as a function of frequency harmonic current

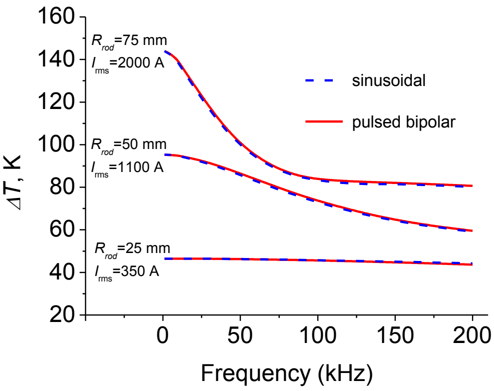

Figure 4: Temperature difference between the rod center and surface as a function of frequency

3. Power supply

Mathematical models and laboratory devices have been realized to implement a high-frequency power supply (frequency higher than 50 kHz). In Figure 5 a schematic structure is presented, in Figure 6 a 3D-model of a high-frequency power supply is shown, and in Figure 7 a photo of a real laboratory device is displayed.

The power-generation-related portion of the inverter model and the control system are based on "SimPowerSystem" (SPS) blocks of MATLAB / SIMULINK. This approach, in contrast to circuit simulation packages, allows to greatly simplify the entire model and to enhance its stability and speed.

The power supply is equipped with a resonant inverter with two cells (sub-modules); moreover, it contains new technology with modern IGBT-transistors, low induction capacitors and a toroidal core from amorphous nanocrystalline alloys. A new high frequency technology with twisted-pair cable is used to decrease reactive and active loss power in the transformer. A high-power cable is used to transmit high-frequency energy; the

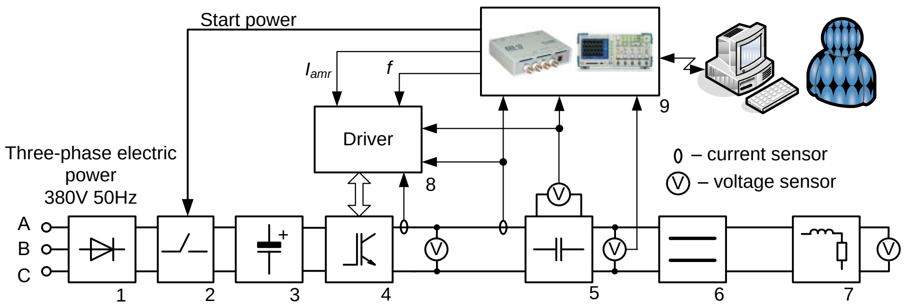

Figure 5: Laboratory device of high-frequency power supply: 1 – power rectifier, 2 – power switch, 4 – inverter, 5 – resonant capacitance, 6 – equivalent high-power high-frequency cable, 7 – equivalent load, 8 – driver, 9 – control unit, I_{amr} – amplitude current reference, f – frequency

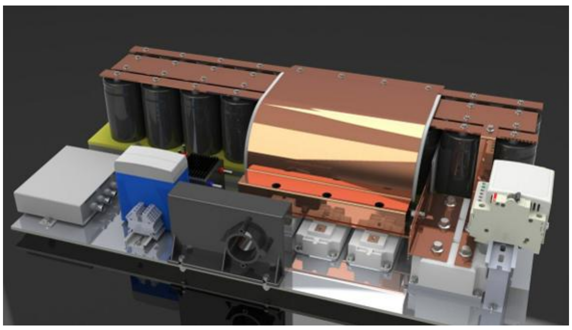

Figure 6: 3D-model of a high-frequency power supply

Figure 7: Photo of a real laboratory device

cable has a plurality of strand pairs where these pairs are bundled so as to run in parallel to each other and the individual wires of the strands are twisted (Wallmeier and Niehaus, 2012).
The power supply automatic control system (ACS) includes two channels (Figure 8): the first includes extreme ACS frequencies; the second includes cascading ACS with PI-controlling of the average current load. Cascading ACS is constituted by two-control loops: the first (main loop) is made of the fast control loop of the amplitude current load; the second includes the control loop of the average current load. The introduction of the fast control loop provides a significant increase in the device reliability for short circuits in the load (i.e. rods fall in Siemens-reactor).
A transient analysis of ACS (Figure 9) provides the following evidences: a transient overshoot is not detected; the stabilization time is the less than 1.5 ms, at an error of less than ±1 % and 30 us, at an error less than ±10 %. The RLC circuit is used in a laboratory device, where R = 0.5 Ohm – load resistance, L = 2 mH – load inductance, C = 4 uF – resonant capacitor.
The power supply simulations highlighted that ± 50 % change in the parameters of the RLC-circuit does not result in a significant decrease of the quality control. Consequently, the ACS has the necessary control robustness.
Experimental evidence has shown that the transformer current secondary winding (Figure 10) and burden is sinusoidal out of the direct component, under the pulsing voltage in the output of a power supply (Figure 11), at a frequency from 20 to 100 kHz, without sacrificing the inverter effectiveness more than 3 %.

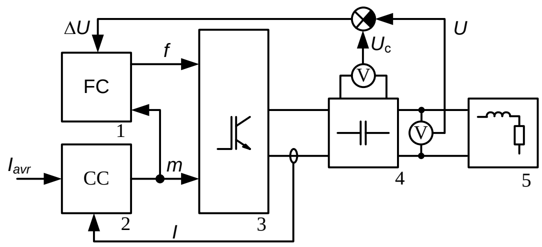

Figure 8: Control system of high-frequency power supply: 1 – frequency control, 2 – current control, 3 – inverter, 4 – resonant capacitance, 5 – equivalent load, U – load voltage, U_c – capacitance voltage, ΔU – error voltage, f – frequency pulse, I_{avr} – average current reference, m – pulse width

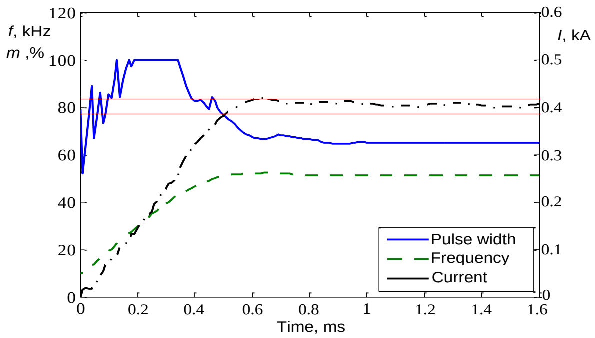

Figure 9: Experimental time evolution of current, frequency and pulse width

4. Conclusions

Different alternative current shapes have been analyzed in order to reduce the internal temperature gradient of the polysilicon rods of Siemens reactor. Simulations have shown that the most effective current in realizing the skin effect in polysilicon rods is a harmonic and bipolar pulse current with frequencies above 50 kHz. Simulations and experimental research by laboratory devices has afforded the possibility to study a high-frequency power supply with the following parameters: average load current from 0 to 1 kA; voltage from 1 kV to 200 V; active load power higher than 200 kW; efficiency higher than 95 %. High-frequency power supplies can be used in induction furnaces with long electrical lines for saline solution heating in pyro-chemistry processes to purify fission material from other fusion side-components (in this case the current frequency is more than 50 kHz). Moreover, power supply can be used in the compact induction furnaces of chemo-metallurgical plants.

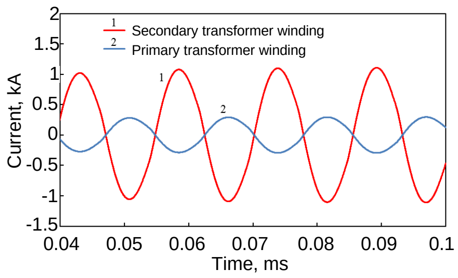

Figure 10: Experimental current shape on the secondary and primary transformer winding

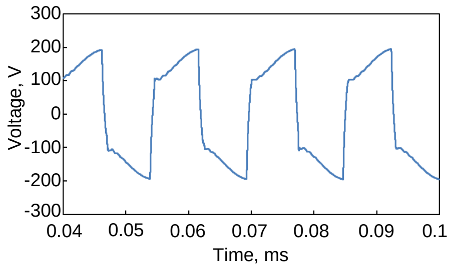

Figure 11: Experimental voltage shape on the out of power supply

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