High Temperature Heating Control using Three Phase Silicon Carbide (SiC) Heaters

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Abstract---Electric heating is most commonly used in many industrial applications, especially where conventional source of energy is not available or not practical. Industrial heating is an evergreen topic for research and development. Innovations never end in this particular field. Apart from other heating methods, electrical heating occupies major portion of the segment. Especially resistance heating plays a critical role with its numerous advantages. Nicrome is the most popular electrical resistance heating material but used up to only 600 to 700°C. For high temperature up to 1600°C, Silicon Carbide (SiC) heating elements are more preferred due to its typical high temperature withstand capacity. Unfortunately, SiC heating elements are sensitive to thermal shock. They offer negative temperature co-efficient of resistance in initial phase of heating. It means their resistance decreases with the increase of temperature. This particular characteristic makes them difficult to control. They tries to draw more current from the supply line and results in more I^2R loss and abrupt thermal shock. With conventional methods of heating control, these typical characteristics deteriorate the performance of SiC heating elements over a period of working life.

Keywords: AC voltage controller, electric heating, reliability, Silicon Carbide (SiC)

I. INTRODUCTION

Electric heating is most widely used in many industrial applications due to enormous advantages like easy control, lower cost, no pollution, high efficiency, lower maintenance etc. Electric heating includes resistance heating, dielectric heating, induction heating, laser heating and plasma heating. Resistance heaters produce heat by passing an electric current through a resistance - a coil, wire, or other obstacle which impedes current and causes it to give off heat. Heaters of this kind have an inherent efficiency of 100% in converting electric energy into heat. Devices such as electric ranges, ovens, hot-water heaters, sterilizers, stills, baths, furnaces, and space heaters are part of the long list of resistance heating equipment. Resistance heating bares some significant advantages over other type of electric heating such as easy installation, versatility, easy control, low maintenance, portability etc. Silicon Carbide (SiC) is common heating element for the heating application upto 1600 °C , can provide rapid heating with very long service life, anti oxidezation, anticorrosion, little deformation, easy installation and maintenance.

SiC elements have a high and variable resistivity at room temperature, but this falls with increasing temperature, reaching a minimum at about 700°C. At an element temperature above 700°C, resistivity increases with rising temperature, this variation in temperature co-efficient may deteriorate the heating performance. To obtain the best performance from SiC elements, the power supply must be properly designed for the application. Some means of power adjustment is usually required to cater the resistance changes that will occur with this type of element. AC voltage controllers, employing phase angle control or integral cycle control technique is normally used for this purpose. This paper includes complete design and development of controller for Silicon Carbide heaters.

II. DESCRIPTION OF PROPOSED SYSTEM

All SiC elements increase in resistance during their life in operation [1] and the rate at which this occurs is affected by the following factors:

- Atmosphere surrounding the elements.
- Mode of operation continuous or intermittent
- Furnace operating temperature.
- Element surface loading in W/cm^2.
- Start up procedure.

As a general guide, SiC elements may increase in resistance at a rate of about 5–6% per 1000 hours operating continuously in clean air at a temperature of 1400°C and at about 3% per 1000 hours use at 1000°C. It should be noted that small changes in operating conditions can alter these rates considerably [1]. For designing controller for three phase SiC heaters, it is required to focus on following characteristics and Due to typical characteristics of SiC heating elements, they are very difficult to handle with constant power systems. The most significant aspect is to limit the power supplied to the SiC heating elements. It means that W/cm^2 rating of the heating elements must not exceed. Violation of this may result in failure of heating elements. As this is a pure resistive circuit, equation for power is as (1).

$$P = \frac{V^2}{R} \tag{1}$$

Where P = power (W)
V = applied voltage (V_{rms}, volts)
R = resistance of element (Ω)

To keep power P within limit, either V or R can be changed. But system does not have any control over resistance (R) because R changes with respect to both time and temperature. So, only parameter remaining is to control RMS voltage applied to heater elements. This suggests that for proper control over SiC heating elements, a reliable, efficient and customized three phase AC voltage controller is required. Overall schematic of the prototype design is shown in Fig.1.

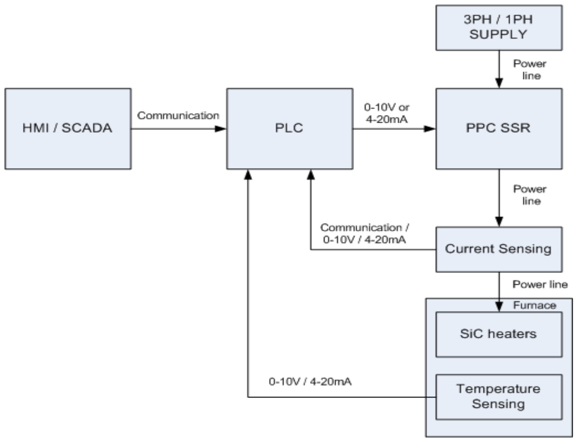


Fig. 1: Overall system block diagram of three phase SiC heater based electrical furnace system.

Actual SiC furnace temperature is measured with a K-type thermocouple connected to a PID temperature controller. PID temperature controller gives percentage power requirement to achieve set temperature in a form of 4-20 mA analogue signal.

Heater controller calculates required firing angle for the thyristors in all three phases in order to achieve required output power.

While deciding firing angle of a thyristor for getting desired output power, care must be taken to control the instantaneous thermal socks on heating elements. Normally, profiling is done in order to heat the element in steps. Temperature performance criteria of SiC heating elements: controller output is considered with these profiling requirements. Additionally, overload limits of percentage full load current can also be defined in the controller, in order to protect the system against excessive high current.

III. DESIGN OF AC VOLTAGE CONTROLLER

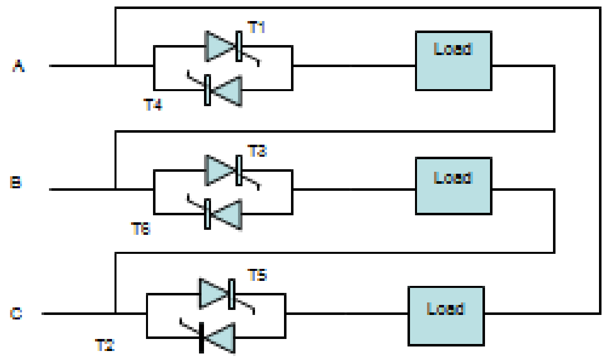
In an AC voltage controller, if a thyristor switch is connected between an AC supply and the load (back to back for full wave), the power flow can be controlled by varying the RMS value of the AC voltage applied to the load.

An AC voltage controller can be considered as a voltage regulator device by which the root mean square (RMS) value of load voltage, hence the power flow; can be set and maintained constant at a certain desired value. Recent developments achieved in the field of power electronics, control techniques and microprocessors have introduced such AC voltage controllers for the applications of power ranges from few watts to fractions of megawatts.

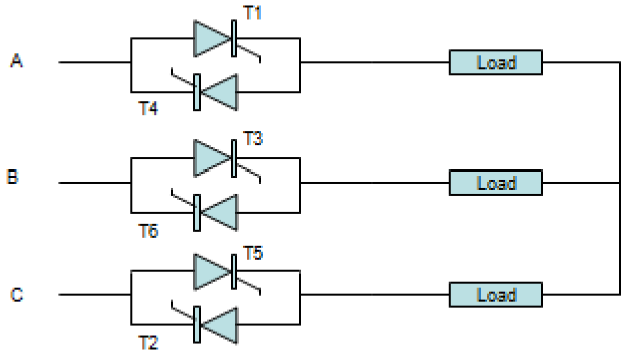
Different configurations of thyristors and resistor elements are possible for AC voltage controller [2]. Among all the configurations, the three-wire inside delta and three-wire star connections without neutral are widely used in the industry. Hence, the technical details of these two configurations are discussed below:

Fig. 2(a) shows three-wire inside delta connected load configuration of AC voltage controller. RMS output voltage of the controller for resistive load can be expressed with equation (2) below [3]. By changing firing angle α, the RMS output voltage of the controller can be changed.

$$V_{0rms} = V_{L,rms}\sqrt{\frac{1}{\pi}\left(\pi-\alpha+\frac{\sin 2\alpha}{2}\right)}\, for 0 \le \alpha \le 180^0 \ldots(2)$$



(a)



(b)

Fig. 2: Configurations of AC voltage controller: (a) Three-wire inside delta, (b) Three-wire line-controlled star.

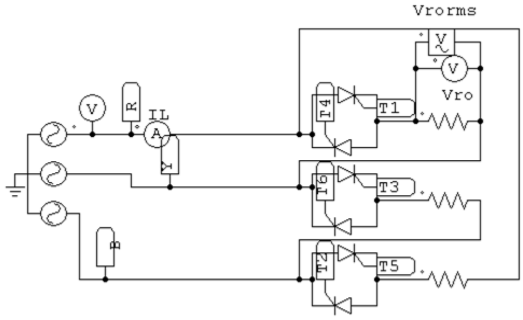
Fig. 2(b) shows a three-wire line-controlled star connected load configuration of AC voltage controller. In this configuration, for firing angle (α) from 0 to 60 degree, three thyristors conducts, from 60 to 90 degree two thyristors conduct, from 90 to 150 degree although two thyristors conduct at anytime, there are periods where there are no thyristors in conduction, and for firing angle (α) higher then 150 degree there is no period for two conducting thyristors. Therefore, the controlling range of delay is 0 to 150 degree in this case. RMS output voltage of the controller for resistive load can be expressed with formulas in equation (3) for various range of firing angles [3]. By changing firing angle α, the RMS output voltage of the controller can be changed.

$$\left.\begin{array}{l} V_{0rms} = V_{L,rms}\sqrt{\frac{2}{\pi}\left(\frac{\pi}{6}-\frac{\alpha}{4}+\frac{\sin 2\alpha}{8}\right)}\, for 0 \le \alpha \le 60^0 \\ V_{0rms} = V_{L,rms}\sqrt{\frac{2}{\pi}\left(\frac{\pi}{12}-\frac{3\sin 2\alpha}{16}+\frac{\sqrt{3}\cos 2\alpha}{16}\right)}\, for 60^0 \le \alpha \le 90^0 \\ V_{0rms} = V_{L,rms}\sqrt{\frac{2}{\pi}\left(\frac{5\pi}{24}-\frac{\alpha}{4}+\frac{\sin 2\alpha}{16}+\frac{\sqrt{3}\cos 2\alpha}{16}\right)}\, for 90^0 \le \alpha \le 150^0 \end{array}\right\} \ldots(3)$$

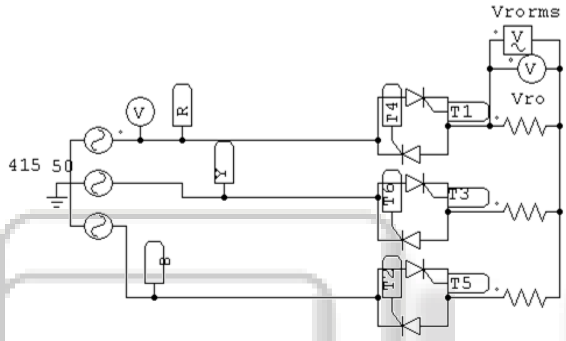
Control circuit for both these configurations should be designed to accept required percentage power output requirement from a PID temperature controller in 4-20mA form. Arrangement of three step-down transformers connected in delta-star configuration is used to generate synchronising signals for all three phases of AC voltage.

IV. SIMULATION OF AN AC VOLTAGE CONTROLLER

Simulations of a three phase AC voltage controller configurations connected in three-wire inside Delta and Star are carried out in power electronics simulation software package PSIM [4]. The schematic diagrams prepared for this power and control circuits are as shown in Fig.3.



(a)



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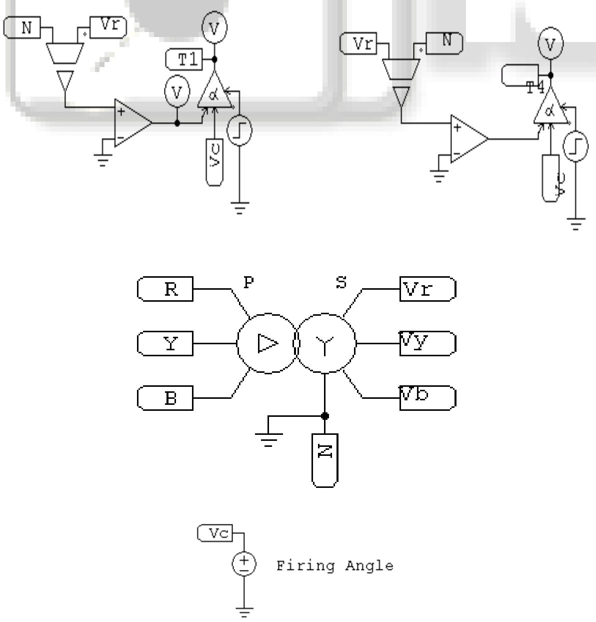
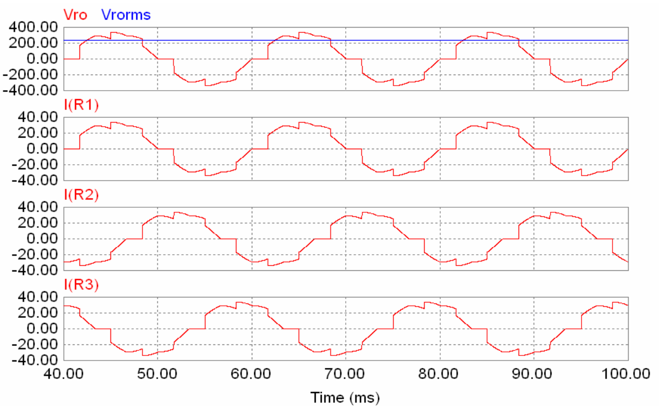
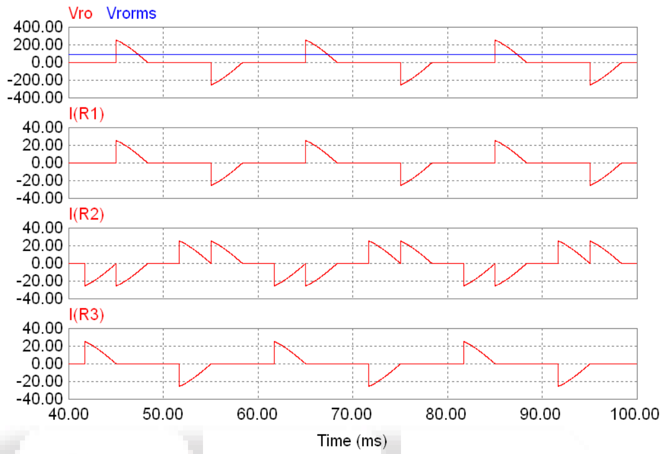


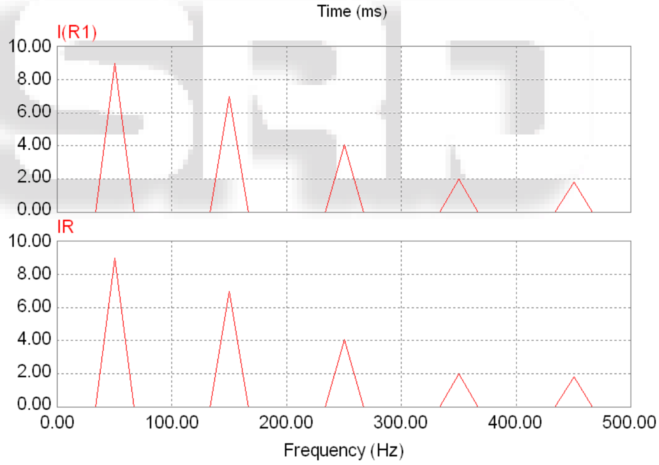
(c)

Fig. 3: Simulation circuit of three phase AC voltage controller: (a) star connected (three phase three wire) arrangement with resistive load, (b) inside delta connected arrangement with resistive load, and (c) control circuit schematic.

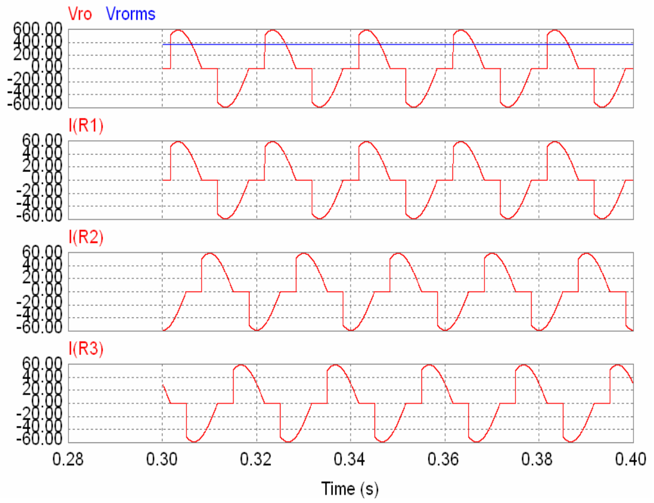
A. Star







B. Inside Delta



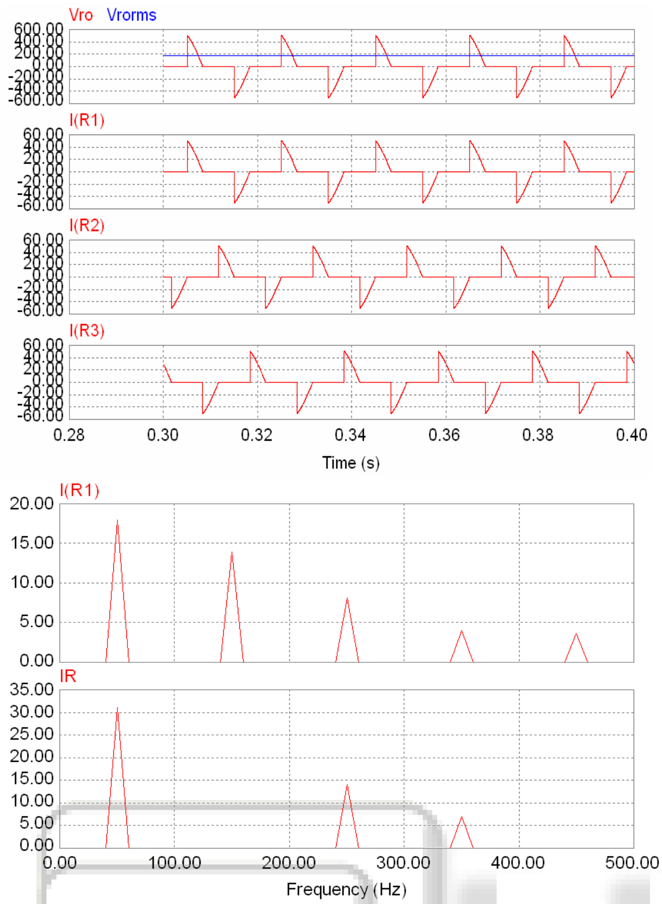


Fig. 4: Simulation results for different firing angles and FFT analysis

Voltage variations, control circuit designing requirements and circuit operation for different firing angles is verified with this simulation. These simulations are extensively run for various conditions of operation and following important conclusions are derived:

In both the configurations, by changing firing angle of the thyristors, voltage applied to load (SiC heating element) changes. Percentage power supplied to the heaters can also be controlled with this variable voltage applied.

For Perfect synchronization of gate pulses, three-phase Delta-Star control transformer is required.

In Star configuration third harmonic appears in the line current waveform. This may lead to pollution of the supply system. Also, it may end-up into the heating of supply transformer and other power components.

In inside delta configuration, third harmonic does not appear in the line current waveform and it circulates among the phases. So, it is less harmonic-polluted configuration as compared to star configuration.

In star configuration, maximum voltage across each heating element is less than the line to line supply voltage. In inside delta configuration, maximum voltage across each heating element is full line voltage. Proper choice of heating element or transformer at input is required for applying rated voltage to heating elements.

Fig.4 shows few simulation results for star and delta configuration at different firing angles. FFT analysis of supply current waveform is also shown. Voltage variation with change in firing angle for both star and delta configuration is observed and relation expressed in equation (2) and (3) is verified. Elimination of third harmonic in delta configuration is verified with FFT analysis of line current waveform.

SiC elements resistance changes with temperature, with life in operation, and based on atmosphere surrounding the elements. So, it is a non linear load for controlling power supplied to the elements. Three numbers of CTs and PTs are connected in each phase to judge the value of resistance offered by element in a particular situation. Based on these feedbacks, the controller algorithm adjusts firing angles in all three phases in order to supply constant power in each phase and in turn to produce constant heating. Algorithm also takes care of all protective features required for overall system including short circuit protections. After successful testing of controller with the test setup explained earlier the controller is tested with real SiC heaters. SiC heating arrangement of 36 kW is setup, which has total 6 SiC elements of 9 kW each. In each phase, two SiC elements are connected in parallel. Thyristor module (Semikron SKKT 250/16 E) and series fuse module of higher capacity are used in this configuration. Fig.5 shows the photograph of this 36 kW furnace system.

(a)

(b)

(c)

(d)

Fig. 5: Test setup of 36kW SiC heating system components: (a) SiC elements and thermocouple assembly; (b) 800^0 furnace setup; (c) heater controller; and (d) thyristor fuse modules.

A 36 kW SiC heating system is developed and experimented for getting furnace temperature of 800^{0}C. The system is tested for various temperatures profiling while staring the furnace and in a normal operation of maintaining constant temperature. Artificially the situation of overload and short circuit are created and system performance to protect the overall setup is tested. Typical heater element voltage waveform captured is as shown in Fig. 6 in steady state operation.

Fig. 6: Photograph of typical voltage waveform.

Over the month of operations, it has been observed that the failure rate of SiC heating element decreases due to less stressed powering to the element and heating life of the system improves.

V. Conclusion

Digital controller for laboratory module of a 1.5 kW three phase AC voltage controller and a 36 kW real SiC heating system is developed and experimented up to furnace temperature of 800^{0}C. Features like temperature rising profiling, good start up routine, power controlling algorithm and protection features help in increasing the reliability of the system and also increase the life of the SiC heating elements. A normal AC voltage controller with good digital control helps in increasing reliability of SiC heating furnace.

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References

[1] Kanthal Globar SD Elements , "Technical Data Manual", SiC elements manufacturer, Web page: http://www.kanthal.com
[2] H. A. Ashour and R. A. Ibrahim, "Comparison Analysis of AC Voltage Controllers Based on Experimental & Simulated Application Studies", ICCES Egypt, pp. 79-84, November 2006.
[3] W. Shepherd, Thyristor Control of A.C. Circuits. St. Albans, England: Crosby Lockwood Staples, 1975.
[4] Powersim Technologies. PSIM Version 6.0, "Power Electronics Simulations, User Manual", Powersim Technologies, Vancouver, Canada, Web page: http://www.powersimtech.com.
[5] J. A. Kay, R. H. Paes, G. Seggewiss, and R. G. Ellis, "Methods for the Control of Large Medium-Voltage Motors: Application Considerations & Guidelines," IEEE Trans. Industry Applications, Vol. 36, No. 6, pp. 1688-1696, November/ December 2000.
[6] M. G. Solveson, B. Mirafzal, and N. A. O. Demerdash, "Soft-Started Induction Motor Modeling & Heating Issues for Different Starting Profiles Using a Flux Linkage ABC Frame of Reference", IEEE Trans. Industry Applications, Vol. 42, No. 4, pp. 973-982, July/August 2001.

