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# Correction Algorithms in Computerized Power Control System for Induction Heating

## 1. Introduction and problem statement

Among many different applications, induction heating has also been proposed for heating of rotating steel cylinders used in various technological processes in paper, textile and other industries [1]. The prototype of such a heating system, being developed in Computer Engineering Department TUL, comprises six inductors fed by high frequency generators [2]. These are thyristor generators with series resonant circuit working in the half bridge resonance mode. Pulse Width Modulation is used for control of generators output power while dc voltage $U_S$ (0–10 V) serves as input signal. Nominal power of each generator is 1 kW and its frequency 20 kHz.

Comparing to typically applied heating methods it occurred to be very efficient one provided that properly chosen temperature control system is applied [1]. The accuracy of the temperature control depends, among others, on static and dynamic properties of mentioned above generators. During trials, the considered generators occurred to be nonlinear and nonstationary elements. Their experimentally measured characteristics are shown in Figure 1.

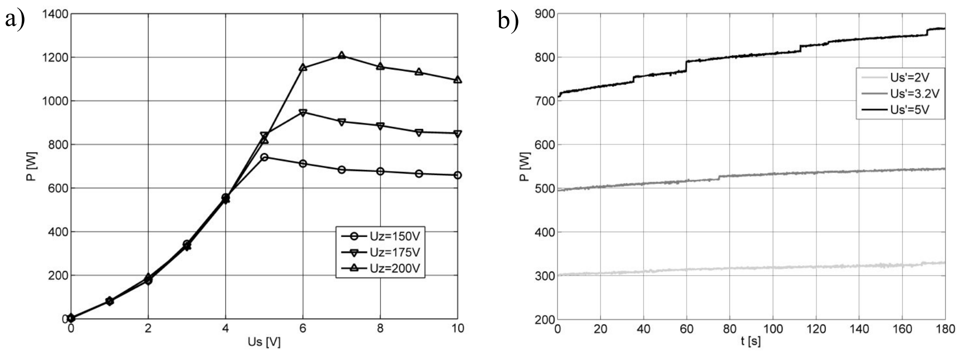


**Fig. 1.** Properties of the high frequency power generator: a) family of nonlinear static characteristics $P = f(U_S)$ for $U_Z =$ const; b) thermal nonstationarity $P = f(t)$ for $U_S =$ const

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In order to ensure good control accuracy these disadvantageous properties of generators have to be eliminated or at least reduced. It can be successfully performed by software procedures realized within computerized data acquisition and processing system which is an inherent part of the considered device.

## 2. Computer-based power control system

Because of several inductors which have to be arranged along the cylinder the control system constitutes multi-input multi-output structure [3]. Such a structure can be conveniently realized and governed within a computerized system equipped with multichannel data acquisition modules. Having this hardware it is quite easy to introduce an additional functionality enabling static characteristic, linearization of generators as well as compensation of their thermal nonstationality. It has been assumed that both these functions can be implemented in a closed loop structure. The part of the system for a single generator is shown in Figure 2.

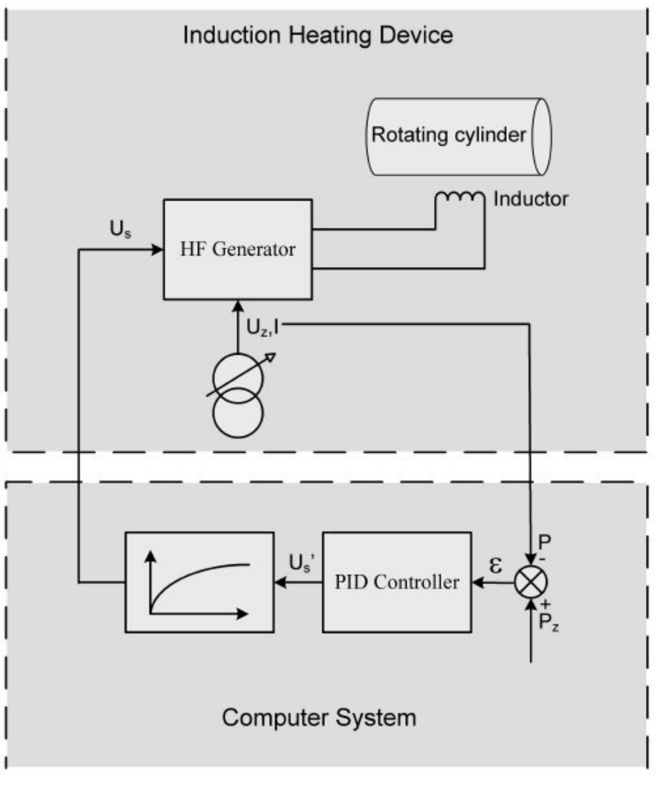


**Fig. 2.** Inductor power supply and computerized control system

It should be mentioned that the loop works in cascade with the main temperature control loop (not shown in Fig. 2) in such a way that the output signal (power) of one loop plays the role of the set-point signal $P_Z$ in the other. Moreover, each loop work with its own sampling period – naturally, sampling frequency of power control loop is a couple of times bigger.

## 3. Linearization of static characteristic

Experimentally measured static characteristic of the power generator, being the relation between the power $P$ and the DC control voltage $U_S$ as shown in Figure 1a, exhibits two types of nonlinearities. First, the saturation of power can be observed when $U_S$ exceeds a certain value – different for different power supply voltage $U_Z$. This is the type of nonlinearity which can not be influenced by any external activity. Second, in the remaining part of $U_S$ range the power $P$ depends on the voltage $U_S$ in nonlinear way as shown in Figure 3a. Typically such a nonlineartity can be compensated by the use of the inverse function of static characteristic as follows:

$$P = f\left(U_S = f^{-1}(U'_S)\right) \tag{1}$$

It means that the linearization can be implemented by the block whose static characteristic $U_S = f(U'_S)$ (Fig. 3b) corresponds to the inverse function of $P = f(U_S)$. Basing on measured experimentally set of points of static characteristic of the generator the inverse function was approximated by the power type function in the form:

$$U_S = f^{-1}(U'_S) = 2.16 \cdot {U'_S}^{0.56} - 0.244 \tag{2}$$

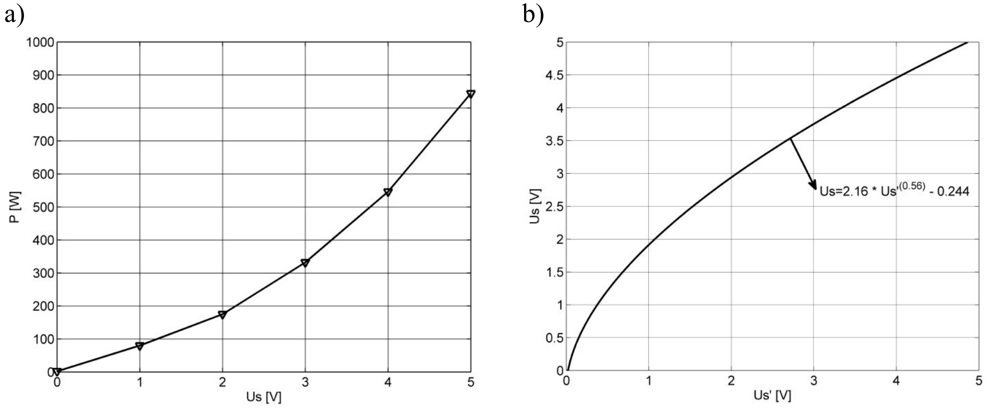


**Fig. 3.** Useful part of the static characteristic of the high frequency generator (a) and the corresponding inverse function (b)

After connection of $U_S = f(U'_S)$ block in serial with power generator as shown in Figure 2 the resulting static characteristic of the whole system remains linear as shown in Figure 4.

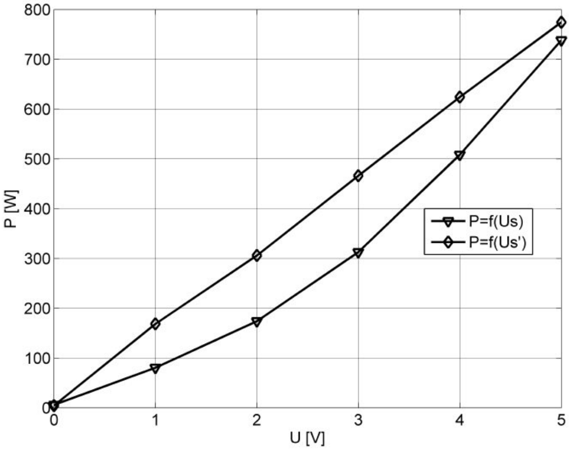


**Fig. 4.** The result of static characteristic linearization

## 4. Nonstationarity compensation

Many experiments performed with the use of the considered prototype device shown that despite of constant value of control voltage $U_S$ the output power $P$ produced by the generator can change in time as given in Figure 1b. Diverse possible reasons of this phenomena can be pointed out, mostly connected with thermal sensitivity of elements.

a) b)

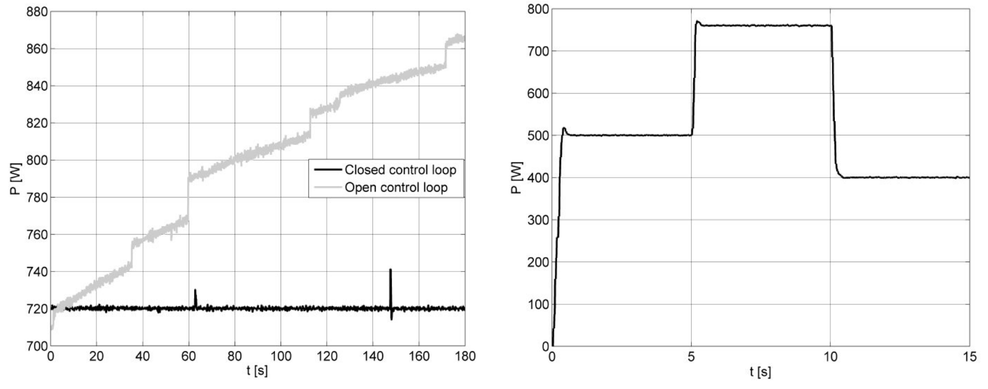


**Fig. 5.** Nonstationarity compensation for $P$ = 720 W: a) and power control accuracy for different set point values $P_z$ = 500 W, 760 W and 400 W

Nevertheless the observed final effect can be significantly reduced by the use of closed loop power control as shown in Figure 2. Due to high efficiency of the generator [1] its power can be easily determined measuring the supply current $I_Z$ and voltage $U_Z$ which are of DC type. In such a structure the power signal can be determined as a controller the PID algorithm was applied. Several identification experiments have been performed using step response and frequency response helped to tune the controller while final values of its parameters were chosen experimentally.

Proposed solution occurred to be very efficient reducing nonstationarity and ensuring stabilized value of the power as shown in Figure 5a. Moreover, the control system exhibits good dynamic properties following vigorously the changes in the set-point as shown in Figure 5b.

## 5. Summary

The prototype device for induction heating of rotating steel cylinder has been considered. Particularly, the properties of high frequency generators were analyzed since they can influence the accuracy of the whole temperature control system. Unfortunately, the generators were identified as nonlinear and nonstationary elements. It was proposed to correct these disadvantages within computerized data acquisition and processing system, which exists already in the considered device. Nonlinearity of the static characteristic of the generator was corrected using its inverse function determined experimentally while nonstationarity was reduced by closed loop control of output power. The solution occurred to be very efficient avoiding any interference in the existing electronic device.

### Acknowledgments

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### References

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