Control of Resistance Spot Welding Using Model Predictive Control

Mostafa Hemmati[1], Mohammad Haeri[2]

[1]Master of Science in Control Engineering
Science and Research Branch of Islamic Azad University, Tehran, Iran
Hemmati_mostafa@yahoo.com

[2]Professor at Faculty of Electrical Engineering
Sharif University of Technology, Tehran, Iran
haeri@sina.sharif.edu

Abstract

Nowadays, the need for industrial processes with sufficient accuracy, efficiency, and flexibility to compete world markets is inevitable. On the other hand, the advent of control techniques and increased computation power of CPUs allow implementation of complex controllers using optimization techniques to provide higher efficiency and economic productivity. Model predictive control refers to a wide range of optimization-based control methods applying explicit models to predict its prospective use. These methods of control compute control signal by minimizing the cost function so that the process output becomes very close to the optimal path. In this paper, we use a new model predictive control technique on a spot welding process as a time varying nonlinear process.

Keywords: Spot welding, Model predictive control, Optimization

1. Introduction

Spot welding is one of the most widely used types of resistance welding. It provides some advantages such as high speed of welding, high compliance for sheets of different thicknesses, proper speed of assembling coordination with other sections and large flexibility to weld various materials such as low carbon steel, coated steel, stainless steel, aluminum, nickel alloys, titanium alloys. Its cost benefits are considerable as well.

In the spot welding process, flow through two pieces of metal causes metal plates melt. When input electric power is cut off, molten materials cool and solidify. The process is performed by a robot welder with a schedule of reckoning the time interval between the cycles of the electrodes, the current flow, and cooling plates. Usually, this time is determined by trial and error and some experimental data samples. In this regard, a rational mathematical model could significantly reduce the number of experimental samples and save the cost and time as well.

For more than 30 years, predictive control has been accepted as the dominant strategy of control in various industries due to high efficiency, constraint handling, and ability to apply on time varying and nonlinear systems. In this method, future control actions are computed by minimizing a cost function so that the process output is very close to the optimal path.

Due to the complication of welding process and interactions among its parameters, there are major problems for assessing the quality of resistance spot welding. In addition, changes in materials composition, coating materials, and process conditions i.e. electrode wear, work piece, rate of cooling water etc., affect the spot welding characteristics.

Electrical current, voltage, and power are used for monitoring and control of dynamic systems. For instance, in [1], some works have been done on these parameters. The authors demonstrated that the curve displacement of dynamic resistance spot weld provides enough information to assess the quality of spot weld. Another work has been carried out to improve the boiling point [2], which dealt with the problem of current transformers saturation. In [3], the problem of monitoring and experimental identification is discussed.

2. Spot resistance welding process

To control a process, one should firstly identify the process dynamics. The estimated model should indicate physical properties and parameters of the system. Throughout this paper an appropriate model is selected and it is assumed that all welding parameters are available.

2.1. Simulation of spot-welding system

In this paper, the enthalpy model introduced in [4] is used to describe the melting process. This model is derived from the first principle of spot welding process.

Temperature depends on electrical conductivity, density, specific heat, and thermal conductivity. This method suffices for materials and weld sheets with different thicknesses. To simulate this model, the numerical solution of partial differential equations for aluminum metal provided in [5] has been carried out (Fig. 1).

According to [6], one of the spot welding quality detection methods deals with the dynamic resistance during the welding.

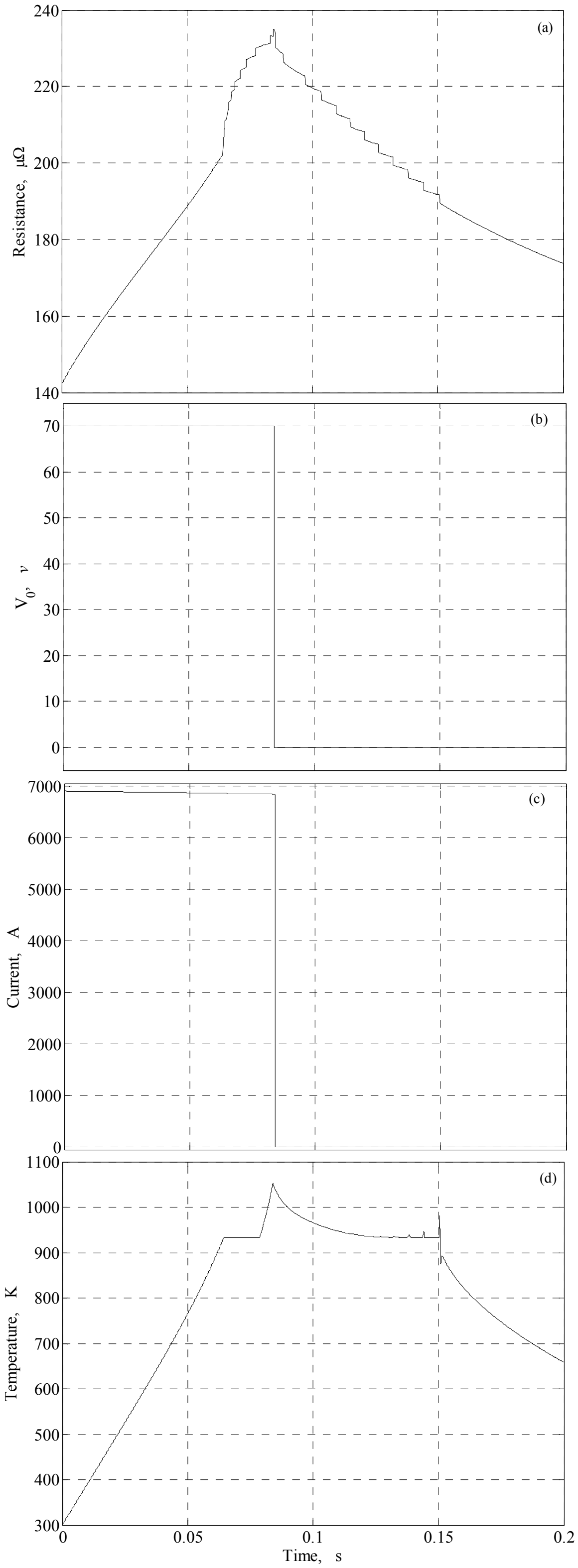

Fig. 1. Spot welding system simulation: (a) Resistance, (b) Voltage, (c) Current, and (d) Temperature.

The optimum temperature of the weld may considerably help one to attain a good quality welding. However, due to the cost of spot temperature measurement (because of need for special cameras), the nearest representative to spot temperature i.e. the resistance of the weld could be considered as the process output. Therefore, one could get feedback from the resistance and control it to achieve a high quality welding.

The block diagram of the spot welding process is shown in Fig. 2. It indicates that the system input is a DC voltage and the output is the sum of the resistances in the welding process.

For simulation purpose, the time and space domains are considered separately. When the temperature reaches the melting point, the input voltage turns off. Then, the plates begin to cool down and solidify. As a result, two plates are stuck each other and spot welding is performed.

All values and equations used in the simulations of this paper are in accordance with [4-6].

2.2. Desired resistance in a spot welding process

To attain a qualified spot welding a desired profile should be designed for the resistance variations during the welding process. In this paper we have considered the one proposed in [6, 7]. This profile is depicted in Fig. 3. As the figure shows, 200 micro ohms resistance is close to the boiling point of the metal. In the melting phase the value will be higher than this. According to this figure the welding operation should be started by applying an initially high voltage. When the resistance reaches a specified value the input voltage should be turned down and then after a while it should be on again for a specific time with appropriate magnitudes. In this paper we employ a model predictive control strategy to generate the desired profile for the resistance variations.

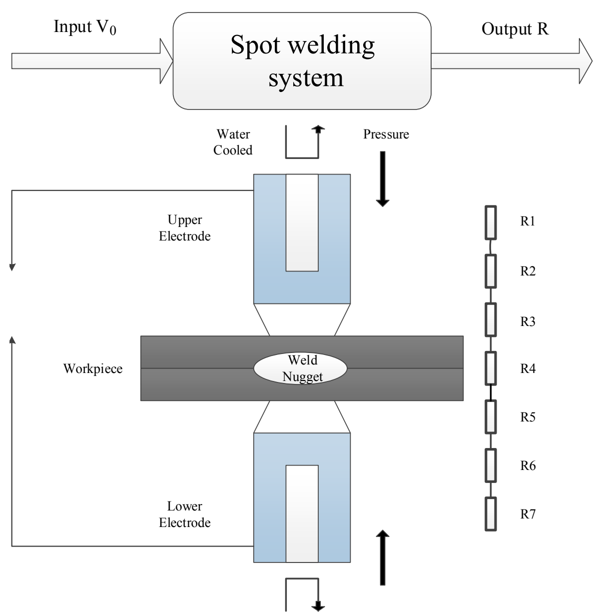

Fig. 2. The block diagram of the spot welding process.

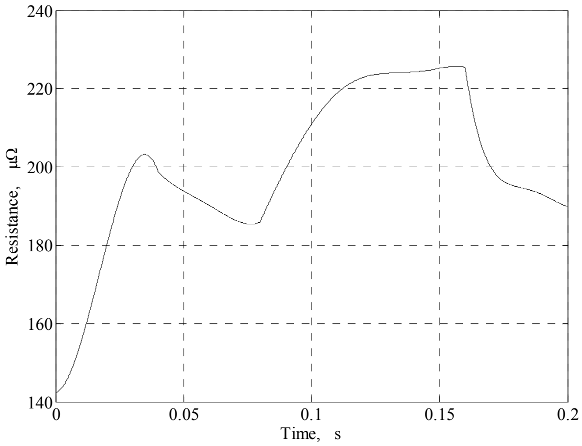

Fig. 3. Desired resistance variation used in this paper.

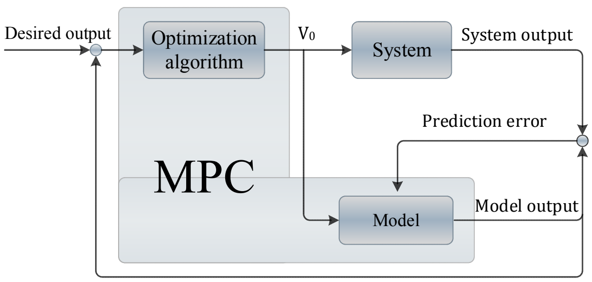

Fig. 4. Block diagram of model predictive control.

3. Model predictive control (MPC) strategies

In general, model predictive control refers to methods of control in which proper control signals are obtained with the aid of a model of process and the minimization of cost function. The common features of all predictive controllers are the use of an explicit model of the process to predict its prospective behavior, solving an optimization problem to determine the required future control actions, and applying some of these calculated control signals to the process. This procedure is repeated at each (or interval) of sampling time(s).

In short, fundamentals of a model predictive controller can be paraphrased as

- Obtaining an appropriate model of process to predict its future behavior.
- Calculating the future control actions through minimizing a cost function.
- Applying some first calculated controls to the process and waiting for the coming sampling time(s).

Figure 4 demonstrates block diagram of the control system using the model predictive control.

To obtain an appropriate model is the first step of implementing an efficient model predictive controller. A complete plan should include a mechanism to obtain the best possible model, so that the dynamics of the model will predict the process output in the future with enough accuracy [8].

3.1. Modeling of the spot welding process

As discussed above, the spot welding system has DC voltage as the input variable and electrical resistance as the output variable. By comparing the resistance curve in Fig. 1a, which is caused in response to a pulse voltage input, with charging and discharging of a capacitor in a simple electrical circuit containg a capacitor and resistance, the spot welding process could be modelled by this simple circuit. When the pulse input is applied, the capacitor begins to charge and when the input is disconnected the capacitor begins to discharge [9]. This idea helps to construct an appropriate model for the spot welding system.

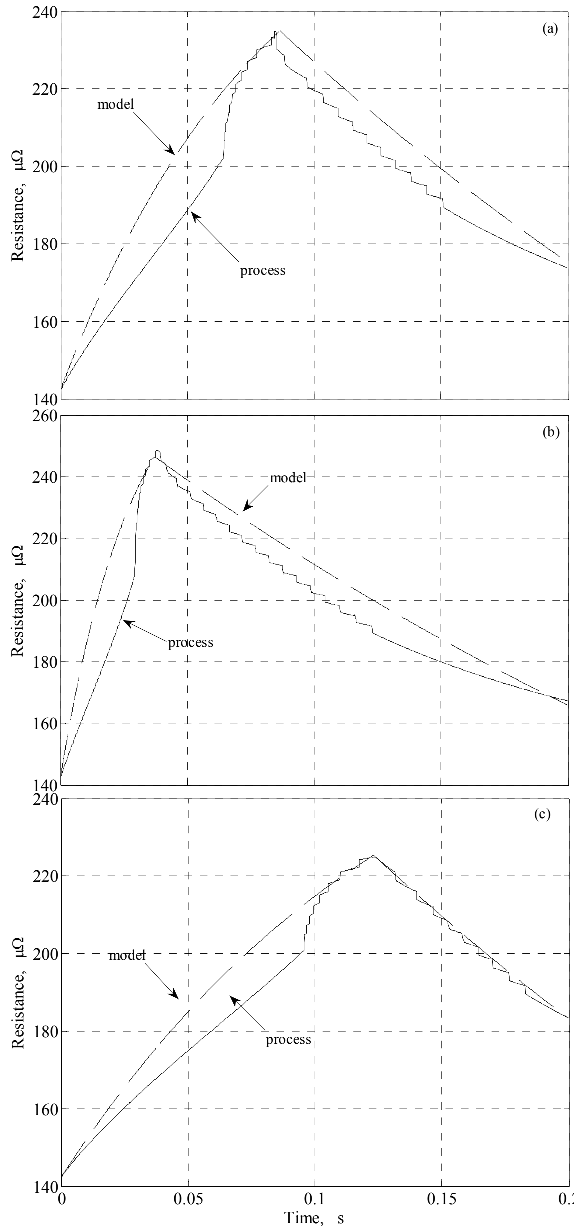

Fig. 5. Output of the model and the spot welding process for different input voltage: (a) 70 volt, (b) 100 volt, and (c) 60 volt.

For different input voltage V_0 the model parameters would be different. In other words, the circuit capacitor and resistor values depend on input voltage. The calculated model is given in (1) and (2). a and b are constant parameters and time constants c_1 and c_2 depend on the input voltage. R_{off} is the value of $R(t)$ at t_{off} which is the time of the input switch.

1- When the input switch is on.

$$R(t) = a + b(1 - e^{-c_1 t}) \quad (1)$$

2- When the input switch is off.

$$R(t) = R_{off} e^{-c_2(t - t_{off})} \quad (2)$$

For example when the input pulse is 70 volts, the parameters' values are as follow.

$$a = b = 142.3\mu\Omega, c_1 = 12.16\text{s}^{-1}, c_2 = 2.58\text{s}^{-1}, t_{off} = 0.084\text{s}$$

The results of this model are shown in Fig. 5 for different values of the input pulse magnitude. Although the model works properly during some period of time, the difference between the model and the system outputs is obvious in some other instances. To improve model performance and reduce the differences, the model is considered for three distinct periods.

1- When the input switch is on but weld has not reached the melting point yet.

$$R(t) = a_1 + b_1 e^{-c_1(t - tt_1)} \quad (3)$$

2- When the input switch is on and weld is in the melting point.

$$R(t) = a_2 + \ b_2 \ e^{-c_2(t - tt_2)} \quad (4)$$

3- When the input switch is off.

$$R(t) = a_3 + b_3 e^{-c_3(t - tt_3)} \quad (5)$$

In brief the modified model for the spot welding process is given by

$$R(t) = a + be^{-c(t - tt)} \quad (6)$$

where, for a pulse input with magnitude 70 volts the parameters' values are as follow

$a_1 = -190\mu\Omega, b_1 = 340\mu\Omega, c_1 = \ 2.63\text{s}^{-1},$
$a_2 = 230\mu\Omega, b_2 = 30\mu\Omega, c_2 = 166.98\text{s}^{-1},$
$a_3 = 140\mu\Omega, b_3 = 80\mu\Omega, c_2 = 10.46\text{s}^{-1},$
$tt_1 = \ 0\text{s}, tt_2 = \ 0.064\text{s}, tt_3 = \ 0.084\text{s},$

As Fig. 6 indicates, the improved model catches the spot welding dynamics more accurately compared to the model presented in Fig. 5.

In this part, an appropriate model of the spot welding process for use in the design of the model predictive controller is derived. This model while is simple displays the dynamics of the process more precisely.

3.2. The optimization algorithm

In a predictive control optimization problem, a cost function is considered to obtain the control law. Use of the following quadratic function is common in the literature.

$$J_k(x(k|k), u) = \sum_{j=1}^{N} \left\| y_p(k + j) - y_{ref}(k + j) \right\|_{P(j)}^2 + \sum_{j=1}^{N} \| \Delta u(k + j - 1) \|_{Q(j)}^2 \quad (7)$$

The second term in the cost function inserts soft constraints on input variations. However, since the input voltage amplitude is confined to 0, 60, 70, and 100 volts, this term would be either zero or one of the mentioned voltage values. It should be pointed out that the second term of the cost function has not been considered in this work. In fact since control input has known values (0, 60, 70, and 100) the question of the control design would be the time period in which one of these inputs is implemented.

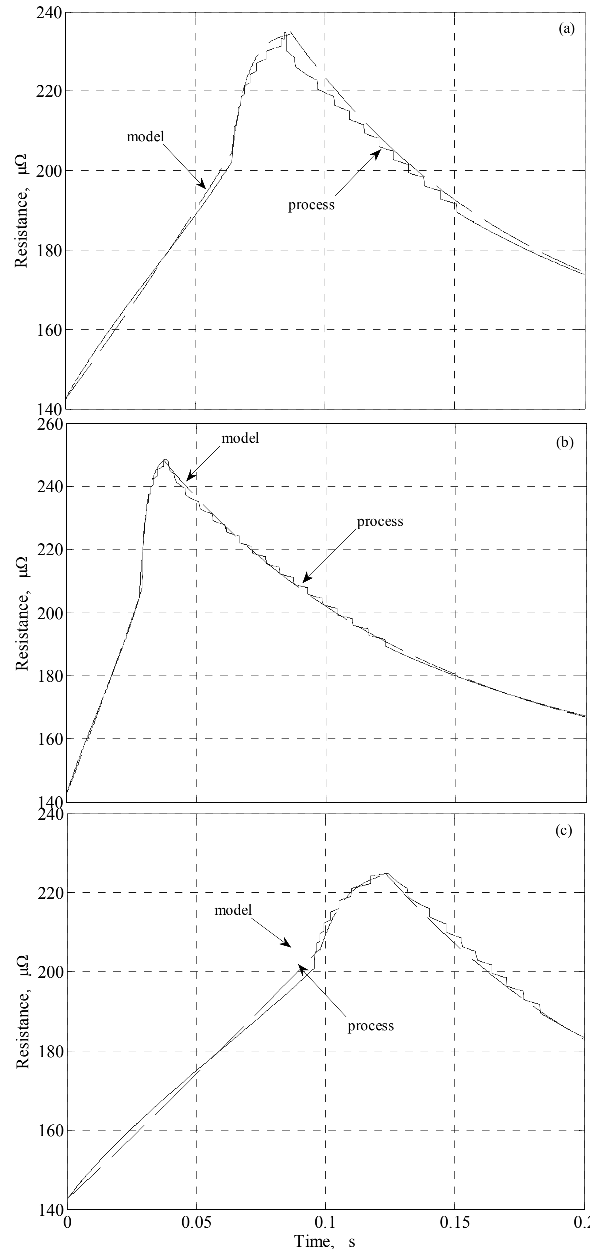

Fig. 6. Outputs of the improved model and the spot welding process for different input voltage: (a) 70 volt, (b) 100 volt, and (c) 60 volt.

4. The simulation results

To make the system more efficient, the sampling time should be small enough, so that the dynamics of the process is included properly. On the other hand, it should be large enough in order to implement the predictive controller online. Here, the sampling time (T_s) of 0.02 seconds was chosen. Using the improved model and the described optimization algorithm, the most optimal solution, obtained online at every time interval, is applied to the process. The results are shown in Figs. 7 to 9.

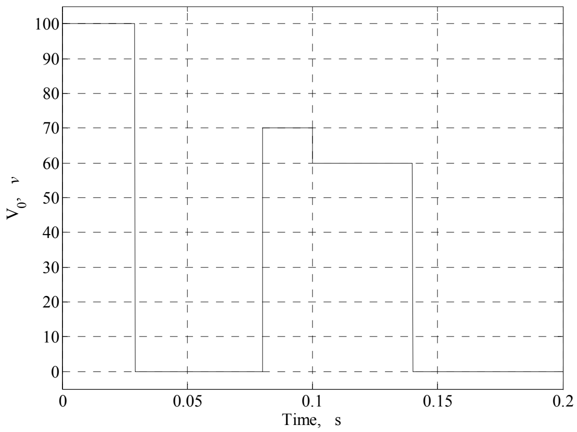

Fig. 7. Optimal control signal u.

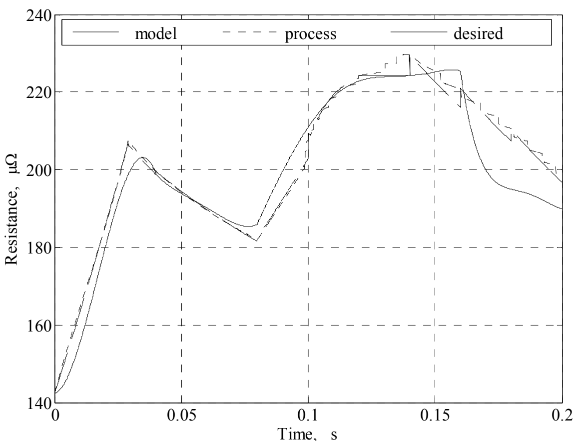

Fig. 8. Responses of the closed-loop system, model, and the desired output.

The calculated control signal is shown in Fig. 7. Figure 8 indicates how the closed loop system follows the profile of the desired resistance which generates a qualified spot welding. Figure 9 illustrates the difference between the desired and actual values. As shown in Figs. 8 and 9, the closed loop performance degrades as the welding process reaches to its end. Note that the defined optimization is solved at each sample time kT_s from this time up to 0.2. Then at $k = 0$ there are 10 (0.2/0.02) degrees of freedom to minimize the cost function. At the last sample time there would be only one degree of freedom ($u(0.18)$). This of course is the main reason for the performance degradation at the last sampling times.

Comparing the model and process responses reveals that the model was able to properly cover the process dynamics during the welding course.

5. Conclusions

In this work, a new model for the spot welding process has been introduced which is appropriate to use in model predictive controllers. This model covers the process dynamics adequately while has simple structure to be used in the control design. The control results obtained based on this model indicate proper tracking of desired profile for spot resistance determined experimentally and represents a good quality welding.

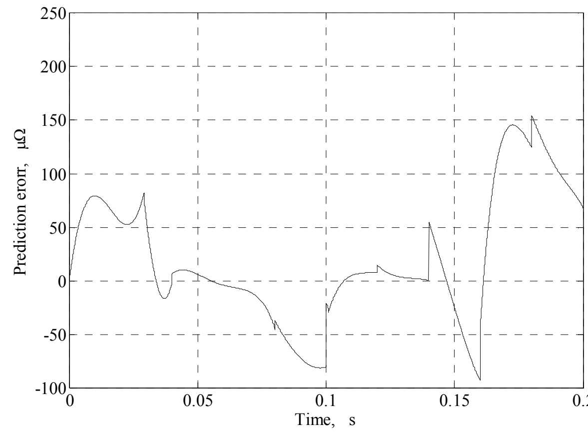

Fig. 9. Resistance prediction error.

References

[1] C.Y. Tseng, Y.Ch. Chen, and T.F. Wang, "Quality monitoring for micro resistance spot welding," 12th IFToMM World Congress, Besançon (France), June 18-21, 2007.

[2] B. Klopcic, D. Dolinar, and G. Stumberger, "Advanced control of a resistance spot welding system", IEEE Transactions on Power Electronics, vol. 23, no. 1, January, 2008.

[3] F.J. Garza and Manohar Das, "Identification of time-varying resistance during welding," Instrumentation and Measurement Technology Conference, the 17th IEEE, vol. 3, pp 1534-1539, 2000.

[4] K.T. Andrews, L. Guessous, S. Nassar, S.V. Putta, and M. Shillor, "A one-dimensional spot welding model," Journal of Applied Mathematics, Article ID 17936, p.p. 1-24. 2006.

[5] D.J. Browne, H.W. Chandler, J.T. Evans, P.S. James, J. Wen, and C.J. Newton, "Computer simulation of resistance spot welding in aluminum-part II," Welding Journal, vol. 74, 417-s, 1995.

[6] S.F. Ling, L.X. Wan, Y.R. Wong, and D.N. Li, "Input electrical impedance as quality monitoring signature for characterizing resistance spot welding," NDT&E International , vol. 43, no. 3, pp. 200-205, 2010.

[7] H. Zhang and J. Senkara, Resistance Welding: Fundamentals and Applications, CRC Press, Taylor and Francis Group, 2006.

[8] E.F. Camacho, and Bordons, Model Predictive Control in the process industry, Springer Technology & Engineering 1995.

[9] J. Bird, Electrical Circuit Theory and Technology, Elsevier Science & Technology, 2007.