# On Microprocessor-Based Arc Voltage Control for Gas Tungsten Arc Welding Using Gain Scheduling

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*Abstract* In a recent paper, Bjorgvinsson *et al.* (1993) propose a gain-scheduling approach for regulating the arc voltage of gas tungsten arc welders. Whilst the proposed realisation appears to be inappropriate, following some straightforward modifications it is shown that a realisation is obtained which achieves linear closed-loop dynamics regardless of the rate of variation of the system.

## 1. INTRODUCTION

In a recent paper, Bjorgvinsson *et al.* (1993) observe that for gas tungsten arc welders the relationship between the arc voltage, length and current is highly nonlinear under certain operating conditions. With the aim of compensating for this nonlinearity, and thereby attaining uniform performance across a wide operating envelope, Bjorgvinsson *et al.* (1993) propose a gain-scheduling approach for regulating the arc voltage.

However, little analysis of the resulting controlled system is presented. In particular, the slow variation requirements usually associated with a gain-scheduled design are not addressed. Moreover, whilst it is known that the realisation adopted for a gain-scheduled controller can have a substantial influence on the performance achieved (see, for example, Leith & Leithead 1996,1998), this issue is largely ignored.

In this note, the choice of an appropriate controller realisation is discussed; in particular, the influence of this choice on the slow variation conditions associated with gain-scheduling. The note is organised as follows. In section 2, some modifications are proposed to the controller realisation adopted by Bjorgvinsson *et al.* (1993). The dynamic behaviour of the resulting controlled system is analysed in section 3 and, on the basis of this analysis, the addition of a feedforward term within the controller is discussed in section 4. The conclusions are summarised in section 5.

## 2. GAIN SCHEDULING

The arrangement considered by Bjorgvinsson *et al.* (1993) is as follows (see figures 1 and 2). The vertical position of the welder is adjusted *via* a servo-motor. The dynamics of the servo-motor are linear, with $K_m/(s+a_m)$ the transfer function relating servo input voltage to motor output angular velocity, $\dot{\theta}_m$. Feedback of the angular velocity through a gain, $K_t$, is employed to introduce additional damping to the servo. A measurement of the arc voltage, V, is fed back to an automatic voltage controller (AVC) which adjusts the welder position in order to maintain a specified arc voltage, $V_{ref}$. The arc current, I, is adjusted separately by the operator and a measurement of it is available. As noted previously, the arc voltage, V, is nonlinearly related to the arc length, L, and the arc current, I; namely,

$$V = h(L,I) \qquad (1)$$

The function $h(\bullet,\bullet)$ is invertible such that L may be expressed as a function of V and I; that is,

$$L = g(V,I) \qquad (2)$$

The gain-scheduling approach to compensation of the arc voltage nonlinearity is to incorporate the reciprocal of the voltage 'gain', $\partial h/\partial L(L,I)$, within the AVC and schedule this gain with respect to a quantity, $\rho$, which parameterises the family of equilibrium operating points of the controlled system. In the present case, a practical choice for the scheduling variable, $\rho$, is the vector, $[V \quad I]^T$, where the relationship, (2), is employed to reformulate the scheduled gain as $\partial h/\partial L(g(V,I),I)$.

The control algorithm proposed by Bjorgvinsson *et al.* (1993) places the scheduled gain, $K_{opt}/(\partial h/\partial L)$, inside the servo velocity feedback loop (figure 2). The dynamics of the closed-loop system, when linearised about an equilibrium operating point at which the arc voltage and current are, respectively, $V_o$ and $I_o$, are then described by the transfer function,

$$V/V_{ref} = w_n^2/(s^2+2\zeta w_n s + w_n^2) \qquad (3)$$

where,

$$w_n = \sqrt{K_{opt}K_mK_L} \qquad (4a)$$

$$\zeta = (a_m+K_{opt}K_mK_t/\partial h/\partial L(g(V_o,I_o),I_o))/2w_n \qquad (4b)$$

Whilst the frequency, $w_n$, is constant, the damping, $\zeta$, varies with the equilibrium operating point. Hence, uniform behaviour across the operating envelope is not achieved.

The non-uniform behaviour arises because positioning the scheduled gain within the servo velocity feedback loop introduces nonlinear velocity feedback. Consequently, it is proposed that it is more appropriate to position the scheduled gain outside the servo velocity loop, as shown in figure 3. With this arrangement, the linearised dynamics retain the form, (3), with $w_n$ unchanged but

$$\zeta = (a_m+K_aK_mK_t)/2w_n \qquad (5)$$

now constant as required, where $K_a$ is a constant gain selected, in conjunction with $K_t$, to ensure appropriate damping, $\zeta$.

The foregoing analysis relates to the linearisations at the equilibrium operating points. When the input and initial conditions of the controlled system are restricted such that the operating point of the system remains sufficiently close to equilibrium and varies sufficiently slowly, the stability of the gain-scheduled nonlinear system may be inferred from the stability of the linearisations at the equilibrium operating points (see, for example, Khalil & Kokotovic 1991). In addition, Leith & Leithead (1996, 1998) note that the restrictions on the class of allowable input and initial conditions may, in general, be substantially relaxed by adopting an appropriate controller realisation. When the servo dynamics are sufficiently fast, as is usually the case, the appropriate realisation is that of figure 3 (Leith &

Leithead 1996). More generally, when the servo dynamics cannot be neglected, the controller realisation should be augmented as shown in figure 5 (Leith & Leithead 1996) ($A^{-1}$ is a realisable approximation to the inverse of the servo dynamics, A, such that $A^{-1}A$ has unity transfer function over the control bandwidth).

Using the arc welder model and control specification described in the Appendix, simulated arc voltage step response time histories are presented in figure 4 for the control configuration of Bjorgvinsson *et al.* (1993) (figure 2) and the modified control configuration of figure 3. With the control configuration of Bjorgvinsson *et al.* (1993), the dependence of the damping on the arc current, I, is clearly evident. In contrast, with the control configuration of figure 3 it can be seen that the damping is invariant with respect to arc current level, as required.

## 3. NONLINEAR ANALYSIS

Gain scheduling theory usually requires a slow variation constraint on the controlled system, corresponding to a restriction on the class of allowable inputs and initial conditions. In this section, the slow variation constraint is investigated for the realisation of figure 5 and, when appropriate, figure 3.

Although the plants are obviously quite different physically, the structure of the nonlinear differential equations, describing the arc welding system of Bjorgvinsson *et al.* (1993), is similar in certain respects to that of the wind turbine system investigated by Leith & Leithead (1997). Moreover, the controller realisations of figures 3 and 5 have a similar structure to that is employed in a widespread, and remarkably successful, approach for accommodating the nonlinear aerodynamics of wind turbines. Adopting, therefore, the approach of Leith & Leithead (1997), the dynamic behaviour of the arc welding system may be analysed as below. (It is noted that the analysis here is based on the nominal dynamics of the arc welding system. Robustness is not considered by Bjorgvinsson *et al.* (1993) and no information is provided regarding the degree of uncertainty associated with the model employed. Whilst not investigated here, it is noted that robustness is considered further, albeit in the context of wind turbine regulation, by Leith & Leithead (1997)).

The arc voltage nonlinearity is,

$$V = h(L,I) \tag{6}$$

It follows that, differentiating (6),

$$z(t) = \frac{\partial h}{\partial L}(L(t),I(t))\frac{dL}{dt} + \frac{\partial h}{\partial I}(L(t),I(t))\frac{dI}{dt} \tag{7a}$$

$$V(t) = \int z(s)ds \tag{7b}$$

It is stressed that the expression, (7), is simply a reformulation of the nonlinear relation, (6), and entails no loss of information. Hence, (7) is valid over the same range of operating conditions as (6). Moreover, it is noted that in (7) the partial derivatives, $\partial h/\partial L$ and $\partial h/\partial I$, are time-varying. Consequently, although similar in form, the representation, (7), is quite distinct from the Taylor series linearisation, about a specific operating point $(L_o,I_o)$, which is only valid in a small region of operation about $(L_o,I_o)$ and for which the partial derivatives are constant. Reformulating the voltage nonlinearity as in (7), it is evident that, owing to the particular realisation and scheduling variables adopted, figure 5 is equivalent to figure 6. Hence, it can be seen that the gain-scheduled controller partially linearises the voltage nonlinearity. This linearisation property is clearly strongly dependent on the controller realisation adopted. Controller realisations which do not achieve linearisation, such as that proposed by Bjorgvinsson *et al.* (1993), lead to a closed-loop system for which the nonlinearity is unnecessarily strong and, consequently, to slow variation requirements which are unnecessarily restrictive.

Of course, the linearisation which is achieved by the proposed controller is only partial and a slow variation restriction remains. Owing to the dependence of $\partial h/\partial I$ on the arc length, an implicit nonlinear feedback loop exists from the arc voltage to the arc current disturbance and the control loop is, therefore, still nonlinear. Provided the arc current varies sufficiently slowly, then the nonlinear feedback is weak and the gain-scheduled controller achieves, as required, closed-loop dynamics which are essentially linear. As noted previously, this slow variation restriction is, in general, weaker than that associated with the realisation of Bjorgvinsson *et al.* (1993).

## 4. ADDITION OF FEEDFORWARD

The foregoing analysis indicates that the proposed gain-scheduled controller imposes a restriction on the allowable rate of variation of the arc current, $\dot{I}$. However, it is also evident from the analysis that when a measurement, or an estimate[1], of $\dot{I}$ is available, the controller may be augmented with feedforward of the arc current disturbance, as shown in figure 7, to obtain linear closed-loop dynamics regardless of the rate of variation of the arc current. The addition of feedforward to the proposed gain-scheduled controller therefore removes completely the restriction to slowly-varying arc current. Of course, the feedforward does not, in practice, cancel exactly with the arc current disturbance and a residual nonlinear feedback to the arc current disturbance remains. However, depending on the degree of cancellation attained, the nonlinearity of the feedback, and consequently the slow variation restriction, is weakened (and, in fact, removed under nominal conditions).

Alternatively, the requirement for a measurement, or estimate, of $\dot{I}$ may be avoided by providing pure integral action within the controller rather than employing the servo-motor to provide integral action. The controller is reconfigured as shown in figure 8, wherein the integral action of the servo-motor is modified by the addition of suitable position feedback (either from a direct measurement of the angular position, $\theta_m$, or an estimate of the position derived, *via* (2), from the measurements of arc voltage and current). The linearising action of the controller is clearly evident with this realisation.

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[1] An estimate of $\dot{I}$ may, for example, be generated by suitably filtering the measurement of the arc current, I.

It should be noted that, in comparison with figure 2, the controller configuration of figure 8 involves two additional user-specified parameters: namely, $K_a$ and $K_\theta$. The parameter, $K_a$, is only included for compatibility with the arrangement considered by Bjorgvinsson *et al.* (1993) and may be chosen, without loss of generality, to be unity. Owing to the cancellation by $A_\theta^{-1}$, the position feedback gain, $K_\theta$, may, in general, be freely selected. However, when the bandwidth of A is sufficiently large compared to the bandwidth of the arc voltage loop (which is almost always the case), the position feedback gain, $K_\theta$, may be chosen to ensure that the bandwidth of $A_\theta$ is large, in which case the controller may be simplified since the inverse, $A_\theta^{-1}$, is not required.

Using the arc welder and control specification described in the Appendix, simulated arc voltage time histories are presented in figure 9 for the control configurations of Bjorgvinsson *et al.* (1993) and of figure 8. The reference arc voltage is varying sinusoidally between 10V and 15V with a frequency of 1 rad/s whilst the arc current is varying co-sinusoidally between 5A and 105A with a frequency of 3 rad/s. It should be noted that these current and voltage variations are merely employed to illustrate the control performance and are not necessarily realistic. With the control configuration of Bjorgvinsson *et al.* (1993), the influence of the variations in arc current on the voltage response is clearly evident. In contrast, with the controller configuration of figure 8, it can be seen that the arc voltage response is decoupled from the arc current variations.

## 5. CONCLUSIONS

The selection of an appropriate realisation of gain-scheduled controller for voltage regulation of gas tungsten arc welders is considered. On the basis of the details provided, the realisation proposed by Bjorgvinsson *et al.* (1993) appears to be inappropriate. However, following some straightforward modifications, a realisation is obtained for which the slow variation restrictions associated with the gain-scheduling approach are somewhat weaker. Furthermore, it is shown that the addition of feedforward can, in fact, enable these slow variation restrictions to be relaxed entirely. Uniformly linear closed-loop dynamics are thereby achieved regardless of the rate of variation of the system.

## REFERENCES


Bjorgvinsson, J.B., Cook, G.E., Andersen, K., 1993, Microprocessor-Based Arc Voltage Control for Gas Tungsten Arc Welding Using Gain Scheduling. *IEEE Transactions on Industry Applications*, **29**, 250-255.

Khalil, H.K., Kokotovic, P.V., 1991, On Stability properties of Nonlinear Systems with Slowly varying Inputs. *IEEE Transactions on Automatic Control*, **36**, 229.

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## APPENDIX

The parameters for the arc welder are as follows:

$$V = \begin{cases} 0.0047I^2 - 0.39I + 13.33 + (0.001I^2 - 0.12I + 16.00)L & I \le 41.5 \\ 15.20 + (0.001I^2 - 0.12I + 16.00)L & I > 41.5 \end{cases}$$

$K_m = 5.0$ rad/Nm s$^2$, $a_m = 0.01$ Nm s/rad

$K_L = 2.0$ inches/rad

The control specification is for a critically damped arc voltage response with bandwidth of 50 rad/s. Specifically, the controller parameters employed are $K_{opt}$=25.0, $K_t$=0.96 for the controller configuration of figure 2; $K_{opt}$=25.0, $K_a$=1.0, $K_t$=2.0 for the controller configurations of figures 3,5,7 and 8. In figure 8, the additional parameter, $K_\theta$, is equal to 50.0.

It is noted that insufficient data is provided by Bjorgvinsson *et al.* (1993) to enable their results to be reproduced. Whilst the voltage nonlinearity employed here is similar to that in figure 4 of Bjorgvinsson *et al.* (1993), it is stressed that the foregoing values are approximate and do not represent any particular arc welder.

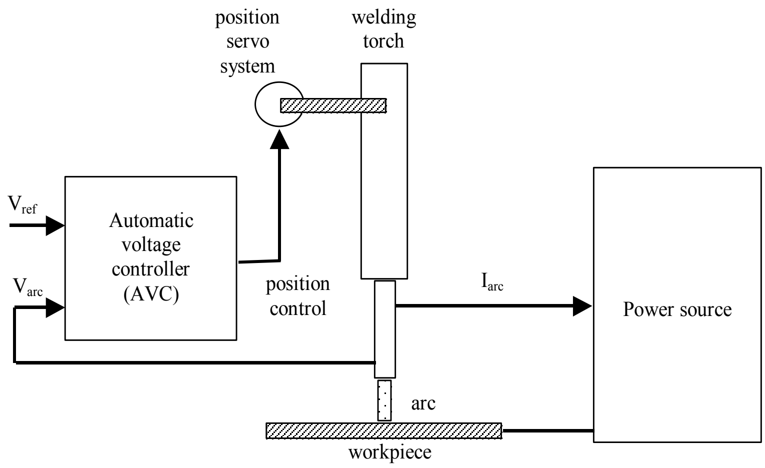


**Figure 1** Welder schematic (adapted from figure 1, Bjorgvinsson *et al.* 1993).

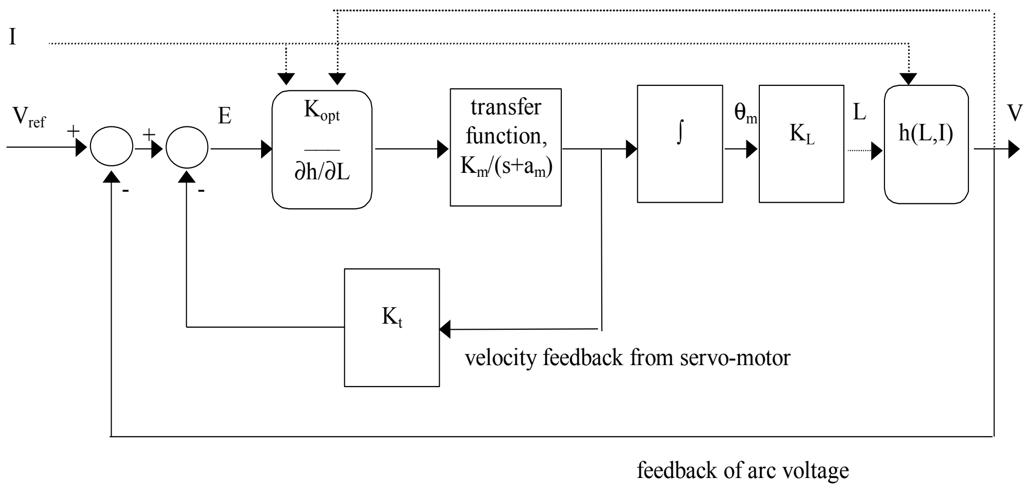


**Figure 2** Arrangement considered by Bjorgvinsson *et al.* (1993)[2].

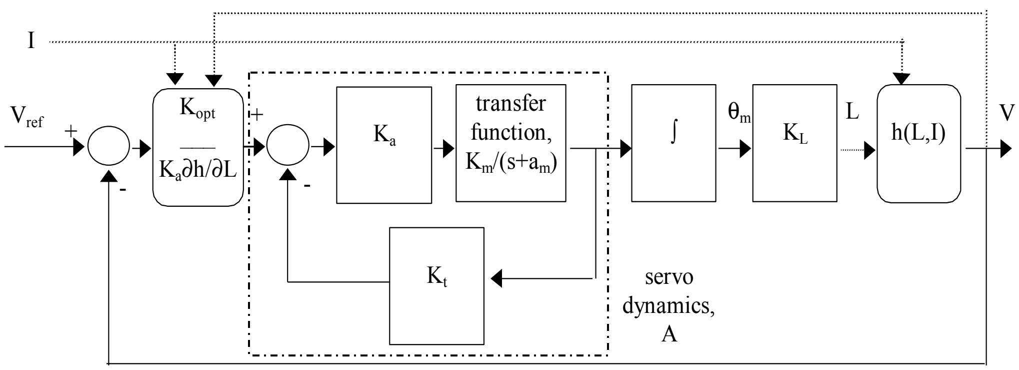


**Figure 3** Alternative arrangement with scheduled gain positioned outside servo velocity feedback loop[2].

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[2] The current measurement transducer is neglected in this diagram

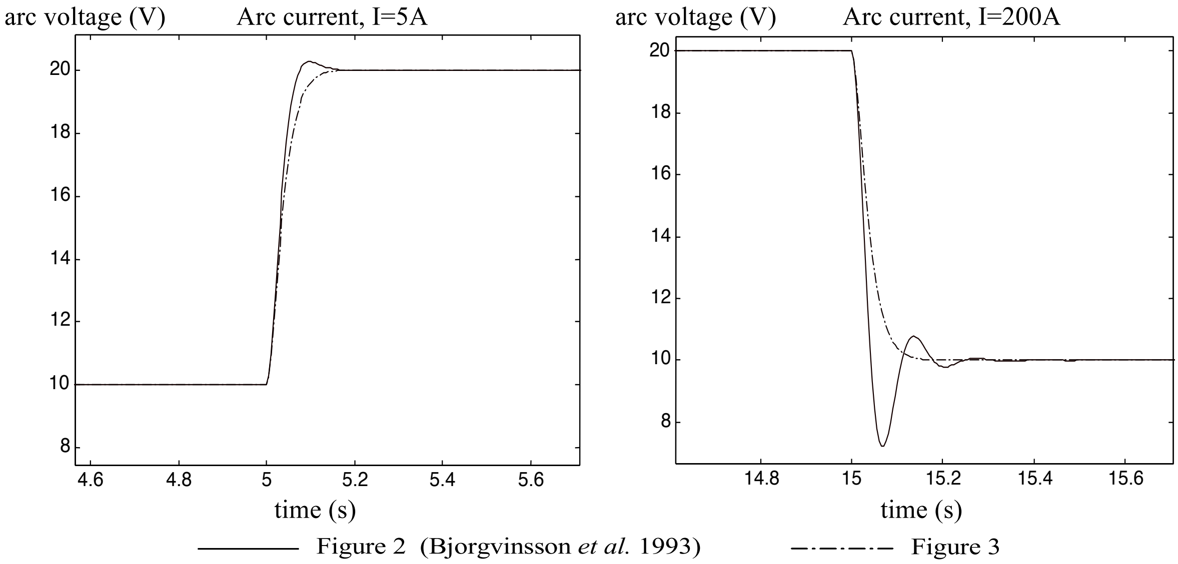


**Figure 4** Simulated arc voltage step responses for the control configurations of figure 2 and figure 3.

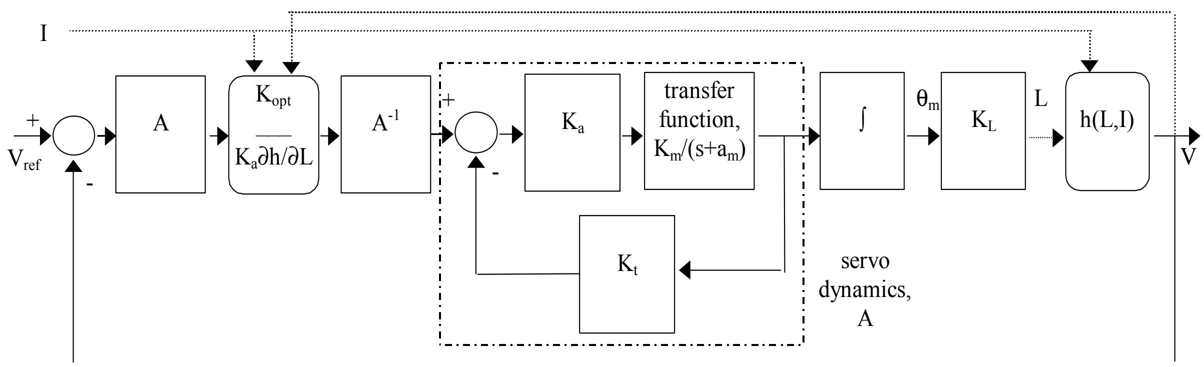


**Figure 5** Compensation for servo dynamics with scheduled gain positioned outside servo velocity feedback loop[2].

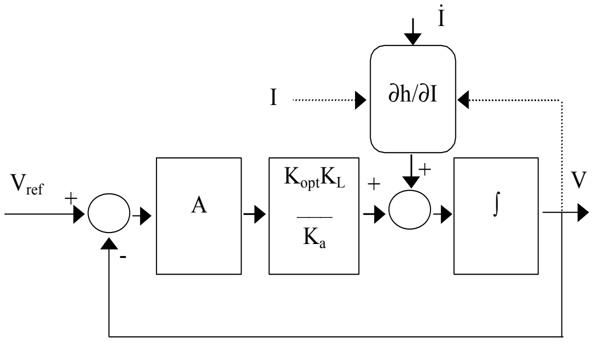


**Figure 6** Reformulation equivalent to the approach depicted in figure 5[2].

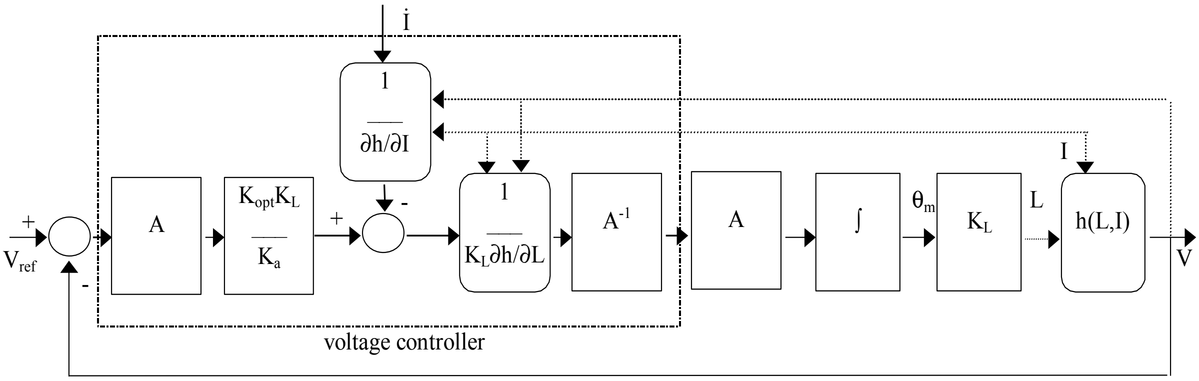


**Figure 7** Gain-scheduled controller with feedforward[2].

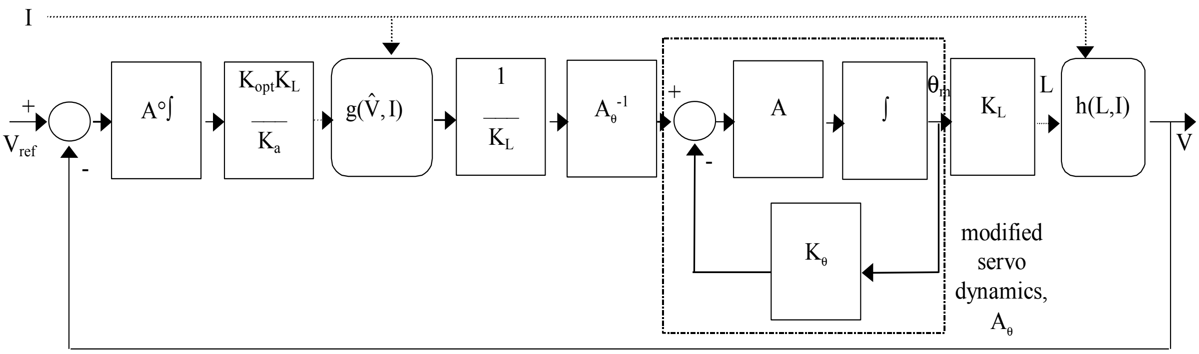


**Figure 8** Reformulation of feedforward controller[2] which does not employ $\dot{I}$.

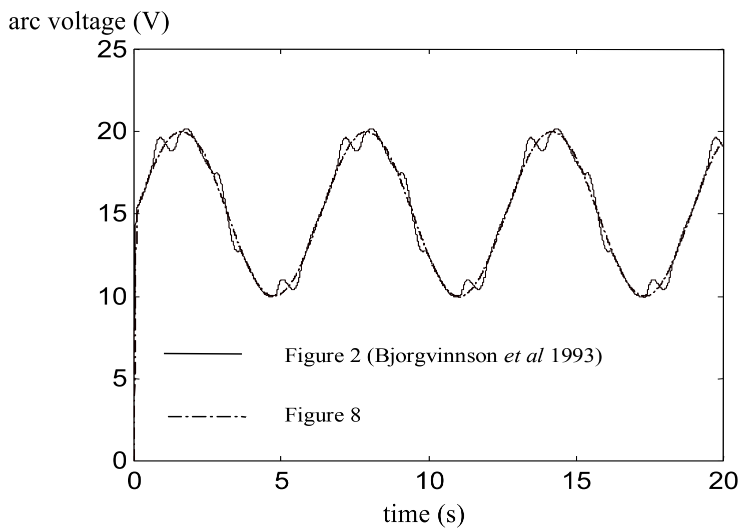


**Figure 9** Simulated arc voltage responses for the control configurations of figure 2 and figure 6.