Self-Tuning of the PID Controller for a Digital Excitation Control System

Kiyong Kim, *Member, IEEE*, Pranesh Rao, *Member, IEEE*, and Jeffrey A. Burnworth, *Member, IEEE*

***Abstract*—This paper proposes an indirect method for self-tuning of the proportional, integral, and derivative (PID) controller gains. Some of the modern voltage regulator systems are utilizing PID control for stabilization. Based on given excitation system parameters, several PID tuning approaches are reported. Since in general, these parameters are not available during commissioning, specifically the machine time constants, this lack of information causes a considerable time delay and cost of fuel usage for commissioning the automatic voltage regulator (AVR). To reduce the commissioning time and cost, the excitation system parameters are automatically identified and the PID gains are calculated using well-developed algorithms. Recursive least-square (RLS) with linearization via feedback is proposed to identify the system parameters. The performance of the proposed method is evaluated with several generator sets. With self-tuned PID gains, commissioning is accomplished very quickly with excellent performance results.**

***Index Terms*—Digital voltage regulator, feedback linearization, generator excitation, recursive least square, self-tuning of the PID controller.**

I. INTRODUCTION

An optimally-tuned excitation system offers benefits in overall operating performance during transient conditions caused by the following: 1) system faults; 2) disturbances; or 3) motor starting. During motor starting, a fast excitation system will minimize the generator voltage dip and reduce the I^2R heating losses of the motor. After a fault, a fast excitation system will improve transient stability by holding up the system and providing positive damping to system oscillations. Additional advantages include the following: 1) improved relay coordination; and 2) first swing transient stability. A well-tuned excitation system will minimize voltage overshoot after a disturbance and avoid the nuisance tripping of the generator protection relays.

Modern excitation control systems are constructed using either static or rotary excitation. The voltage source of an excitation control system is derived from the generator terminals (shunt configuration) or from a separate external power source.

Manuscript received May 15, 2009; revised November 9, 2009; accepted November 23, 2009. Date of publication May 10, 2010; date of current version July 21, 2010. Paper 2009-PSEC-123.R1, presented at the 2009 Industry Applications Society Annual Meeting, Houston, TX, October 4–8, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Power System Engineering Committee of the IEEE Industry Applications Society.

The authors are with Basler Electric Company, Highland, IL 62249 USA (e-mail: kiyongkim@basler.com; praneshrao@basler.com; jeffburnworth@basler.com).

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Digital Object Identifier 10.1109/TIA.2010.2049631

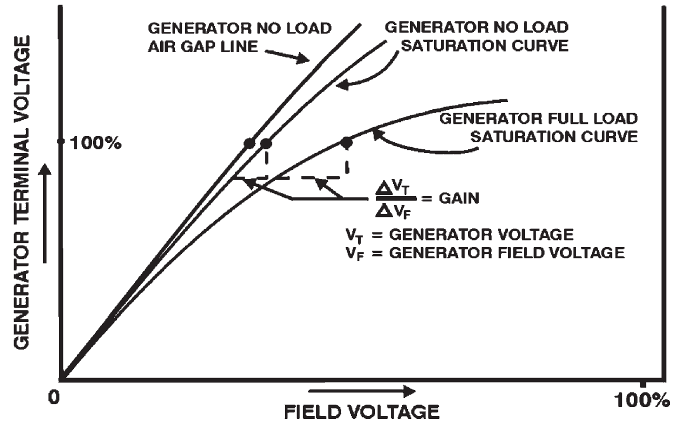


Fig. 1. Generator saturation curve illustrating generator gain.

A linear model is applicable to the excitation control system with an external power input. For a shunt configuration, it is modeled as a bilinear system. A rotary excitation system with a shunt power input is considered here.

The controller gains are determined using several excitation system parameters, such as the voltage loop gain, open-circuit time constants, etc. [1]. These parameters vary not only with the system loading conditions as illustrated by Fig. 1, but also with the system configuration-dependent gains such as the power input voltage. The calculation of loop gain requires several excitation system parameters that are generally not available during commissioning, specifically the machine time constant. This lack of information increases commissioning time [2]. Many times, there is no access to the actual equipment but only to a manufacturer's data sheet, or some typical data set. For this case, the only available measurement to verify the excitation system performance is the combined response of the exciter and generator as shown in Fig. 2. Under these conditions, commissioning of a new voltage regulator becomes a challenging task.

One solution to reduce the commissioning time and cost is to automatically tune the PID controller. The self-tuning controller was introduced in [6]. It continuously identifies time-varying system parameters and adjusts controller gains to minimize a properly selected performance index. Application to the automatic voltage regulators (AVRs) is reported in [7]–[10]. Recently, several particle swarm optimization (PSO)-based algorithms have been successfully implemented to determine the PID controller gains, [4] and [5]. These were developed for the linear system. Furthermore, these methods are not applicable if the time constants of the generator and exciter are not available.

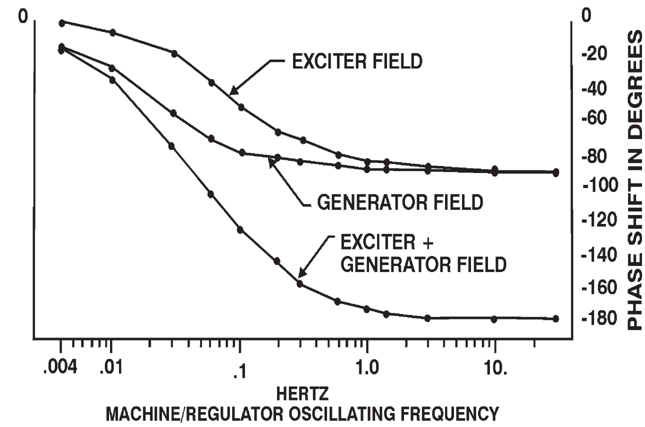


Fig. 2. Phase shift of exciter, generator, and combined system.

North American Electric Reliability Corporation (NERC) standards require the performance of offline tests to verify operation of the generating system to its defined mathematical model on a routine basis. This verification requires the identification of system model parameters.

Thus, it is natural to develop an algorithm to achieve these requirements. This paper proposes an indirect method for self-tuning of the PID controller gains. It is utilized to automatically identify the excitation system parameters and to design the PID controller based on well-developed algorithms [1]. Recursive least square (RLS) with linearization via feedback [3] is applied to identify the excitation parameters in practical environment conditions for a shunt configuration (a bilinear system).

II. Model of Self-Excited Excitation Control System

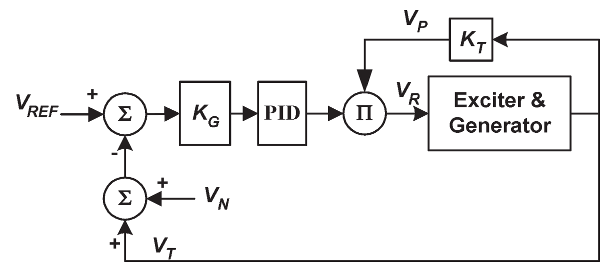
The basic block diagram of a self-exciting excitation control system with the PID block utilized in the AVR control loop is shown in Fig. 3. In addition to the PID block, the system loop gain (K_G) provides an adjustable term to compensate for the variations in the system input voltage to the power-converting bridge. The transfer function $G_c(s)$ of the PID controller may be expressed as

$$G_c(s) = K_G\left(K_P + \frac{K_I}{s} + \frac{K_D s}{1 + T_D s}\right) \tag{1}$$

where

- K_G is the loop gain
- K_P is the proportional gain
- K_I is the integral gain
- K_D is the derivative gain
- T_D is the derivative filter time constant
- s is the Laplace operator
- V_{REF} is the generator voltage reference
- V_T is the sensed generator voltage
- V_N is the noise in terminal voltage sensing
- V_P is the power input voltage
- V_R is the voltage regulator output.

As shown in Fig. 3, the PID controller output is multiplied by the power input voltage (V_P). For the external power input case (not shown above), V_P becomes a constant. Thus, linear system theory can be applied for small-signal stability. If the power input is derived from the generator voltage for the self-excitation application, i.e., $V_P = K_T V_T$ where K_T is a gain that represents a power transformer, the exciter field voltage is the PID control output multiplied by a factor of the generator terminal voltage and the excitation control system becomes a bilinear system.



V_{REF} is generator voltage reference
V_T is sensed generator voltage
V_N is noise in terminal voltage sensing
V_P is power input voltage
V_R is voltage regulator output

Fig. 3. Simplified excitation control system with AVR.

A. Calculation of the RMS Value of Generator Voltage

The generator voltage (V_T) in the above figure is expressed as the rms value, which may be calculated based on the number of samples per period of the nominal generator frequency. If the system frequency varies, the sampling interval should be changed in order to calculate accurate rms and phasor information. A variable interval sampling scheme is utilized in some digital regulators.

B. Consideration of Noise in Generator Voltage

Today's digital voltage regulators are designed to achieve about 0.25% regulation accuracy at rated voltage. Accuracy is mostly determined by the truncation error in the A/D converter and thermal noise in the interface circuits. In general, the calculation error is negligible since all calculations are achieved by a floating-point arithmetic. IEEE Std. 421.5 recommends a 2% step response for testing or analyzing performance of an excitation control loop. Thus, generator voltages due to small perturbation in excitation are measured with a very poor signal-to-noise ratio. For example, the relative accuracy of a 2% step response test may exhibit a 10% error in measurement, which makes it difficult to identify the exciter and generator time constants. This results in very slow convergence which is not compatible with today's fast excitation system requirements.

III. Self-Tuning Strategy

In order to make the self-exciting control system a linear system, a simple feedback linearization loop is implemented as shown in Fig. 4.

The power input voltage is estimated every 50 ms based on the generator rms voltage scaled by the transformer ratio and

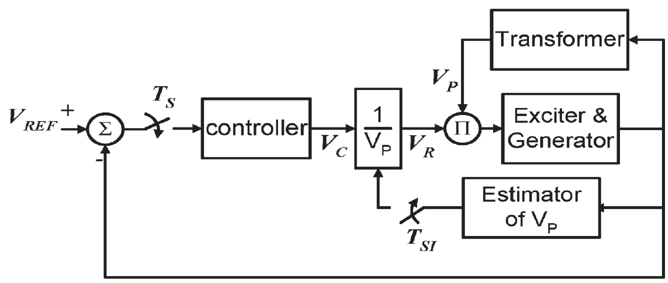


Fig. 4. Feedback linearization of self-excitation control system.

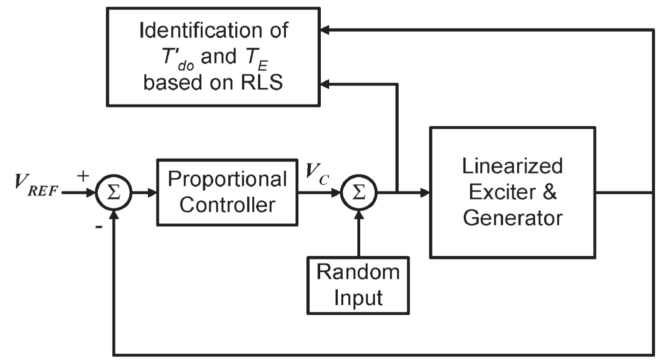


Fig. 5. Identification using RLS.

rated exciter field voltage at no load. The controller output is scaled by the power input voltage to eliminate the bilinear effect. As the sampling time (T_{SI}) of the inner loop decreases, the bilinear characteristic disappears in the system response. The selection of 50 ms has been determined based on the simulation results with time constants of the industrial excitation control system under practical noise environment. With inner loop control implemented, a linear estimation algorithm can be utilized. Thus, the plant transfer function $G(s)$ is approximated as

$$G(s) = K_S \left(\frac{1}{1+sT_E}\right)\left(\frac{1}{1+sT'_{do}}\right) \tag{2}$$

where K_S, T_E, and T'_{do} are the system gain, the exciter and generator time constants, respectively.

A. Estimation of the System Gain

As shown in Fig. 1, the system gain varies with the operating conditions. Note that the system gain is the combination of the following: 1) the power amplifier; 2) exciter; and 3) generator gains. The gain K_G in Fig. 3 is used for compensating variations in the system configuration-dependent gains such as power input voltage (V_P) and saturation effects, i.e., $K_G K_S = 1$.

The gain K_G is estimated based on a steady-state condition near rated generator voltage. This is accomplished using a robust controller that includes a soft start feature. The soft start feature is designed to avoid a large voltage overshoot during voltage buildup.

The PI controller is utilized to achieve a steady-state condition, at which the regulator output and terminal voltage are measured. The steady-state condition is determined when the generator voltage variation is less than 0.005 p.u. for more than 10 s.

The regulator output and generator voltage are utilized to determine the system loop gain K_G. The steps for calculating the loop gain are as follows.

1) Check the residual voltage with zero regulator output.
2) Find the open-loop output corresponding to the residual voltage.
3) Find the regulator output corresponding to the nominal generator voltage using a PI controller.
4) Calculate the loop gain, $K_G = V_R/V_T$ where V_R and V_T are the PI controller output and generator voltage used in the PI controller, respectively.

B. Estimation of the Time Constants

RLS with linearization via feedback is depicted in Fig. 5. A closed-loop control system with proportional gain is used, which makes the system stable as well as it operates continuously in a linear region, i.e., not in the saturation region. The white noise disturbance is added to the P-controller output (V_C). The variance of the white noise is automatically adjusted to maintain the terminal voltage within 0.6–1.0 p.u. The resultant regulator output and generator terminal voltage are sampled every 400 ms and are utilized for estimating the time constants. The closed-loop reference is selected to regulate at 80% of the rated voltage. The actual input to the exciter field is the controller output scaled with an estimate of the power input voltage. Thus, the bilinear characteristic caused by a shunt configuration is canceled and the exciter and generator can be modeled as a linear system.

Using the zero-order hold method to convert from continuous to discrete form, the generator output at the kth sample time $(k = 1, \ldots, N)$ is expressed in terms of the regulator output, u_k and the generator output y_k as

$$y_k = a_{\mathbf{0}} + a_{\mathbf{1}} y_{k-1} + a_{\mathbf{2}} y_{k-2} + b u_{k-1} + b_{\mathbf{2}} u_{k-2} \tag{3}$$

where $a_{\mathbf{0}}$ is used to account for any bias error in the control system. In least square estimation, unknown parameters of a linear model are chosen in such a way that the sum of the squared errors between the actually observed and computed generator voltage is minimum

$$E(\alpha, N) = \sum_{k=1}^{N} \left(y_k - \phi_k^T \alpha\right)^2 \tag{4}$$

where $\alpha^T = [a_1 \quad a_2 \quad b_1 \quad b_2 \quad a_0]$ and $\phi_k^T = [y_{k-1} \quad y_{k-2} \quad u_{k-1} \quad u_{k-2} \quad 1]$. Solving for the system parameter α, we develop the closed-form solution as follows:

$$\hat{\alpha}_k = \left(\sum_{k=1}^{N} \phi_k \phi_k^T\right)^{-1} \left(\sum_{k=1}^{N} \phi_k y_k\right). \tag{5}$$

It is possible to manipulate the above equation into a recursive form, which is more efficient for real-time estimation [3]. The recursive form is given by

$$L_k = P_{k-1} - P_{k-1}\phi_k \left[\phi_k^T P_{k-1}\phi_k + \lambda\right]^{-1} \tag{6}$$

$$P_k = \frac{1}{\lambda}\left(I - L_k\phi_k^T\right) P_{k-1} \tag{7}$$

$$\hat{\alpha}_k = \hat{\alpha}_{k-1} + L_k\left[y_k - \phi_k^T\hat{\alpha}_{k-1}\right] \tag{8}$$

where λ is a forgetting factor between zero and one. The forgetting factor of 0.9 is utilized based on experiments with various generators and the initial value of 30 is used for the diagonal element of the covariance matrix. With the estimated values α, the time constants of the generator and the exciter are calculated as follows:

$$\hat{T}'_{do} = -T_s/\log\left(\frac{\hat{a}_1 + \sqrt{\hat{a}_1^2 + 4\hat{a}_2}}{2}\right) \tag{9}$$

$$\hat{T}'_E = -T_s/\log\left(\frac{\hat{a}_1 - \sqrt{\hat{a}_1^2 + 4\hat{a}_2}}{2}\right) \tag{10}$$

where T_s is the sampling time.

C. Calculation of PID Gains

To simplify the design of the PID controller, we assume that $K_S = 1$, and $T_D = 0$. Thus, the plant transfer function $G(s)$ is given as

$$G(s) = \left(\frac{1}{1+sT_E}\right)\left(\frac{1}{1+sT'_{do}}\right). \tag{11}$$

Two methods are suggested for designing PID controllers [1]. First, the pole-zero cancellation approach is considered. The PID controller design using pole-zero cancellation method forces the two zeros resulting from the PID controller to cancel the two poles of the plant. The placement of zeros is achieved via appropriate choice of controller gains. The open-loop transfer function of the system becomes

$$G_C(s)\cdot G(s) = \frac{K_D\left(s^2 + \frac{K_P}{K_D}s + \frac{K_I}{K_D}\right)}{T'_{do}T_E s\left(s + \frac{1}{T'_{do}}\right)\left(s + \frac{1}{T_E}\right)}. \tag{12}$$

For the pole-zero cancellation, we set

$$K_I = \frac{K_D}{T'_{do}T_E}$$
$$K_P = K_D\left(\frac{T'_{do} + T_E}{T'_{do}T_E}\right). \tag{13}$$

Thus, the transfer function gets reduced to

$$G_c(s)G(s) = \frac{K_D}{T'_{do}T_E s}. \tag{14}$$

The closed-loop transfer function then becomes

$$\frac{C(s)}{R(s)} = \frac{G(s)G_C(s)}{1 + G(s)G_C(s)} = \frac{K_D/T'_{do}T_E}{s + K_D/T'_{do}T_E}. \tag{15}$$

The time response of the closed-loop system to a unit step input is as follows:

$$c(t) = 1 - e^{-\frac{K_D}{T'_{do}T_E}t}. \tag{16}$$

If t_r is the specified rise time which is defined as the time required for the response to rise from 10%–90% of its final value, the value of K_D is obtained by

$$K_D = \frac{T'_{do}T_E \cdot \ln 9}{t_r \cdot K_G}. \tag{17}$$

It can be seen that K_D depends on the plant parameters and the desired rise time. Once we establish K_D, we can calculate K_I and K_P from the equations discussed above.

At first, the idea of pole-zero cancellation might seem academic since the exact pole-zero cancellation is virtually impossible. The root locus plots for cases where the actual and estimated time constants are off by $\pm 20\%$ appear significantly different. Experiment shows that in spite of these differences, the designed controller parameters result in performance that is acceptable for most generator sets with the exciter time constant about one-tenth of the generator time constant.

Secondly, the PID controller is designed via a variation of pole placement method. In this method, the desired closed-loop pole locations are decided on the basis of meeting a transient response specification. In one possible approach, the design forces the overall closed-loop system to be a dominantly second-order system. Specifically, we force the two dominant closed-loop poles to be a complex conjugate pair, say $s = -a \pm jb$, resulting in an underdamped response. The third pole is chosen to be a real pole, say $s = -c$, and is placed so that the natural mode of response from it is five times faster than the dominant poles. The open-loop transfer function $G_c(s)G(s)$ is given as

$$G_c(s)G(s) = \left(K_P + \frac{K_I}{s} + K_D s\right)\left(\frac{1}{1+sT_E}\right)\left(\frac{1}{1+sT'_{do}}\right). \tag{18}$$

The PID controller gains K_P, K_I, and K_D are then analytically determined by solving the characteristic equation

$$\left(K_P + \frac{K_I}{s} + K_D s\right)\left(\frac{1}{1+sT_E}\right)\left(\frac{1}{1+sT'_{do}}\right) = -1 \tag{19}$$

for $s = -a + jb$, resulting in two equations, and $s = -c$ giving the third equation. We thus have three equations with three unknown controller gains which are solved to get these three gains. The controller also results in two zeros. The effect of the zeros on the transient response is compensated by the overdesign and involves a certain amount of trial and error and engineering judgment. The root locus of each method to see the effect of zeros is discussed in [1].

IV. Implementation of Self-Tuning Digital Voltage Regulator

The self-tuning method of a PID controller described in the previous section was derived for a rotary excitation system with the voltage source from the generator terminals (shunt configuration). This technique is also applicable to other types of excitation control systems with some modifications. In order to show its effectiveness and applicability to industrial environment, the proposed algorithm was implemented into an available commercial voltage regulator developed for a small-size generator set (less than 10 MVA). In general, this type of regulator has been designed cost-effectively and the size of memory and computation power are limited.

The voltage regulator consists of the following: 1) a microprocessor and signal conditioning circuits for the generator voltage; and 2) a PWM-controlled regulator output. The generator voltage is sampled with a 10-bit resolution after antialiasing filters. The rms calculation of the generator voltage is calculated every half cycle (8.3 ms for 60-Hz system). The self-tuning algorithm is updated every 400 ms.

During calculation of the system gain K_G, the amplitude of the regulator output is adjusted to maintain the voltage regulation in a linear region at about 80% of the rated generator voltage.

A PC program was developed for a simple user interface to the digital voltage regulator with the self-tuning function. The following features are implemented in the PC program:

1) basic diagnostic functions (wiring and metering calibration);
2) estimation of the loop gain using closed loop with PI controller;
3) estimation of the generator and exciter time constants using RLS;
4) calculation of the PID controller gains using estimated time constants (T_E and T'_{do});
5) step response with real-time monitoring.

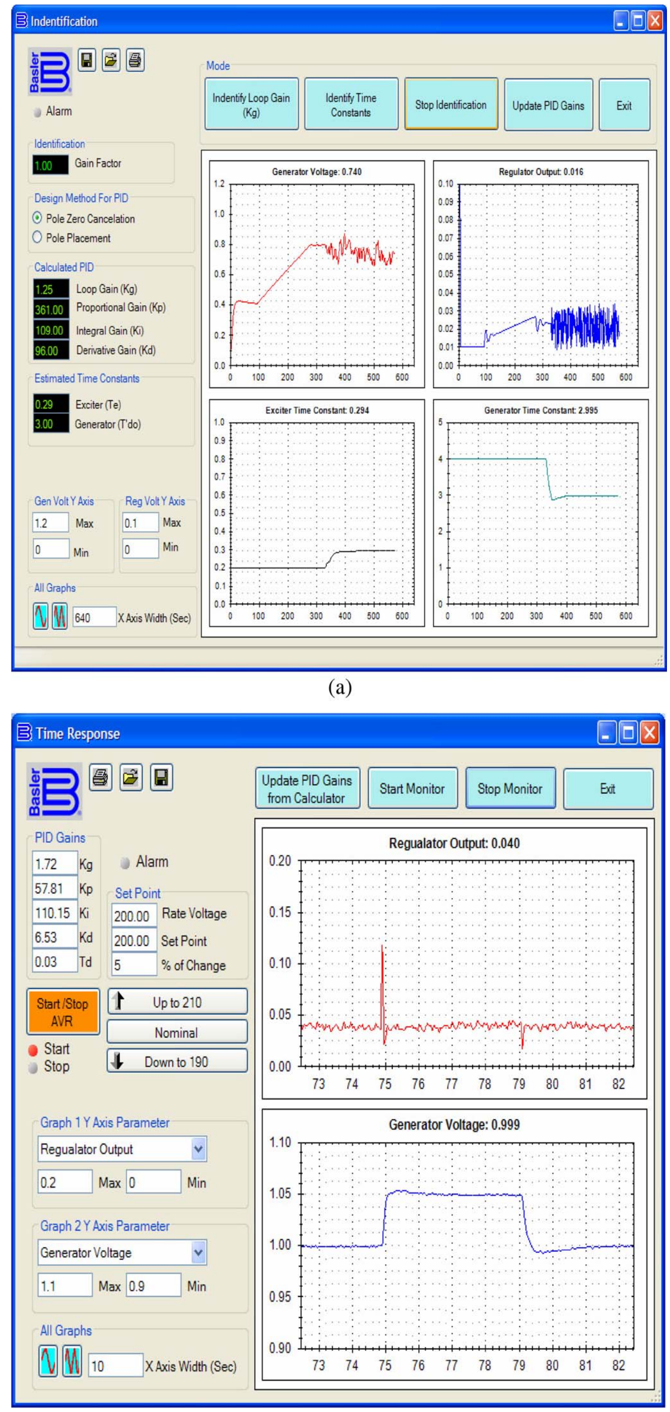
The field engineer activates the self-tuning mode using this PC program. The system parameters (system gain and exciter/generator time constants) are then estimated and the PID gains are calculated using either pole-zero cancellation or pole-placement design methods.

Fig. 6(a) shows the PC program which monitors the system and estimated parameters continuously. A real-time monitoring feature was also implemented to easily evaluate the system performance of the voltage step responses [see Fig. 6(b)]. In Fig. 6, the x-axis is in seconds. The y-axis unit for the generator voltage is per unit and for the time constants is in seconds. The regulator output is in per unit where 1.0 per unit is the maximum PID controller output.

V. Test Results

The performance of the proposed self-tuning algorithm was verified using a simplified first-order exciter and generator simulation models. Estimation results of the proposed method are shown in Tables I–III.

The external power input case (fixed V_P) was tested for comparison with a shunt application case. The results of the two approaches are illustrated in Tables I and II. No significant error is recognized for both cases. With a 10% relative error in the generator voltage, about 30 s was required to converge to the accurate time constants as shown in Table III.



(a)

(b)

Fig. 6. PC program to interface with regulator. (a) Estimation of time constants. (b) Step response with calculated PID gains.

TABLE I
Estimation Results of the Proposed Method for External Power Input

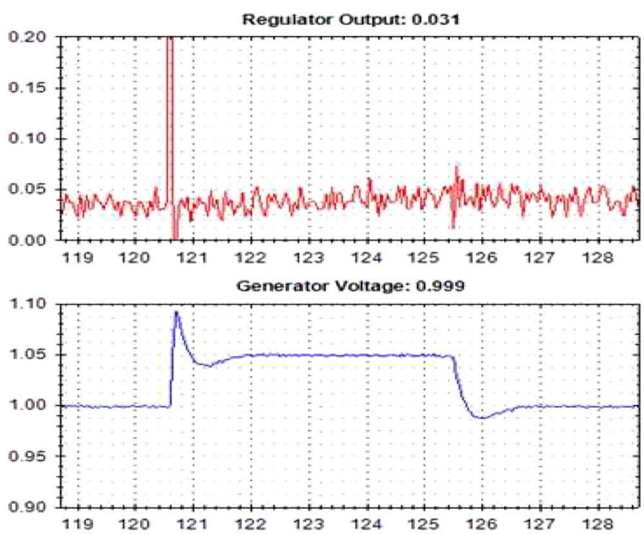
Time constants (T_E, T'_{do})	RLS
(0.15,2.0)	(0.14,1.99)
(0.3,3.0)	(0.29,3.0)
(0.5,4.0)	(0.49,4.0)

TABLE II
ESTIMATION RESULTS OF THE PROPOSED METHOD FOR SELF-EXCITED POWER INPUT

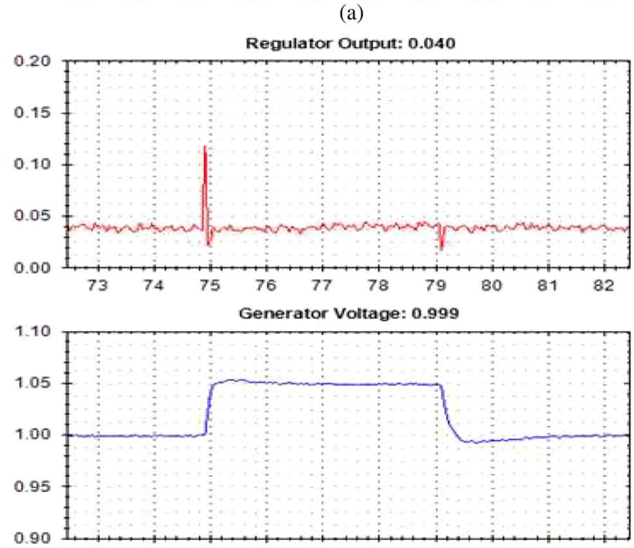
Time constants (T_E, T'_{do})	RLS
(0.15,2.0)	(0.15,1.98)
(0.3,3.0)	(0.3,2.98)
(0.5,4.0)	(0.5,3.98)

TABLE III
ESTIMATION RESULTS OF THE PROPOSED METHOD FOR SELF-EXCITED POWER INPUT WITH 10% RELATIVE ERROR IN GENERATOR VOLTAGE

Time constants (T_E, T'_{do})	RLS
(0.15,2.0)	(0.15,1.98)
(0.3,3.0)	(0.3,2.98)
(0.5,4.0)	(049,3.98)



(a)



(b)

Fig. 7. Comparison of the AVR responses. (a) AVR response with default values. (b) Self-tuned PID gains.

The performance of the proposed self-tuning algorithm was tested using a Diesel-Generating Set, which consists of a 75-kW, 208-Vac, 1800-r/min, 3ϕ synchronous generator. The no-load excitation for this generator is provided by a self-excited 0.3-A, 7-V dc, ac exciter.

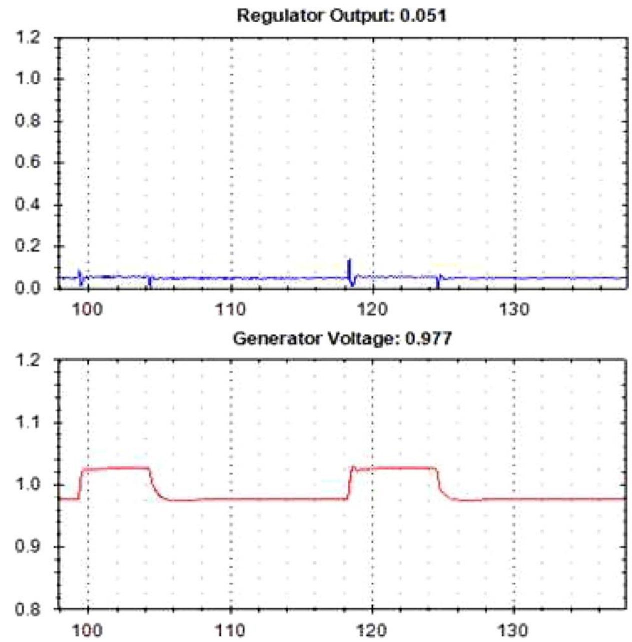


Fig. 8. Step response of gas turbine generator set.

Since the exciter and generator time constants are not available, factory PID gains ($K_P = 200$, $K_I = 600$, $K_D = 30$, and $T_D = 0.0$) were selected that were obtained for another generator by a trial-error method. Since the factory gain for $K_G = 50$ caused a large overshoot, it was reduced to $K_G = 1.0$ to achieve a reasonable response [see Fig. 7(a)]. Voltage step response was carried out to compare the performance of these gains to the self-tuned gains.

Using the PC program that includes the self-tuning features, the self-tuning mode was activated to determine PID gains based on the rising time and estimated parameters (system gain and exciter/generator time constants) using the pole-zero cancellation method ($K_P = 58$, $K_I = 110$, and $K_D = 6.5$). The time constant for the derivative term was selected as $T_D = 0.03$ to reduce the noise effect. Significantly less commissioning time was required to establish the system PID constants using the self-tuning feature.

The voltage step responses of the two methods are illustrated in Fig. 7. The units of *x*- and *y*-axes are the same as in Fig. 6. Fig. 7(a) illustrates a large overshoot which is caused by improper gains. A fast step response with much less overshoot is obtained with the self-tuned gain [Fig. 7(b)]. In Fig. 7, the voltage step up and down responses are asymmetric. The large overshoot in the step up response is caused by an asymmetric high forcing limit. This is a typical response for a rotary excitation control system which has no negative field forcing. For this case, the selection of the proper controller gains is more important.

The proposed method was also tested with a larger generator set that included a gas turbine and a generator rated at 13.8 kV and 15 MVA. The step response using the self-tuned PID gains is illustrated in Fig. 8. With the proposed methods, a fast step response with much less overshoot was obtained within several minutes.

VI. Conclusion

A self-tuning approach of a PID controller using RLS was applied to tune the PID gains of a digital excitation control system. The loop gain was estimated at a steady-state condition of the closed loop with a PI controller. Time constants of the exciter and generator were identified with RLS. Approximately 30 s was required to converge to the time constants with a 10% error of the rms voltage calculation. These parameters were then utilized to establish the PID controller gain. With self-tuning of the PID gains, commissioning of a generator excitation control system can be accomplished very quickly with excellent performance results.

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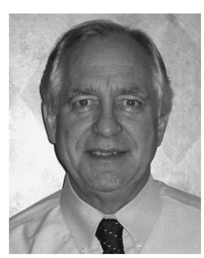
Kiyong Kim (M'97) received the B.S. degree from Hanyang University, Seoul, Korea, in 1979, the M.S.E.E. degree from the University of South Florida at Tampa, in 1991, and the D.Sc. degree from the Systems Science and Mathematics Department at Washington University in St. Louis, MO, in 1995.

He worked for the Agency for Defense Development, Korea, from 1979 to 1988, as a Research Engineer in the areas of system modeling, analysis, design, and simulation. He is currently with Basler Electric Company, Highland, IL. His research interests are in the development and application of computational intelligence techniques for digital excitation control systems, parameter identification, and power systems stability and control.

Mr. Kim is a member of the IEEE Power Engineering, IEEE Industry Applications, and IEEE Computational Intelligence Societies.

Pranesh Rao (M'97) received the B.E. degree in electrical engineering from Bangalore University, Bangalore, India, in 1993, and the M.S. degree in electrical engineering from the University of Missouri at Rolla, in 1997.

From 1997 to 1999, he was with Sprint, Kansas City, MO. Since 1999, he has worked as Principal Engineer for Basler Electric Company, Highland, IL, where he concentrates on research, modeling, and product development in the areas of generator excitation controls, protective relays, and genset controllers. His primary areas of technical interest are power systems analysis, controls and simulation, power electronics modeling and control, digital controls, digital signal processing, and software development.



Jeffrey A. Burnworth (S'76–M'76) received the B.S. degree in electrical engineering from the University of Missouri at Rolla, in 1976.

Since 1977, he has worked at Basler Electric, Highland, IL, in various design and engineering management positions. He is presently the Manager of Technology Development Engineering.

Mr. Burnworth is a member of the IEEE/PSRC and present or past Chairman of several standards development working groups and the Electrical Environmental Subcommittee, and a member of the Industrial and Professional Advisory Council (IPAC) at Southern Illinois University, Edwardsville (SIUE).