KNOWLEDGE AND TECHNOLOGY TRANSFER: NOVEL RESULTS WHILE TEACHING ADVANCED COURSES

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Abstract: Graduate studies in fields of Engineering typically include advanced control theory. In turn, these courses enhance both academic and applied research, hence contributing to combined knowledge and technology transfer, in particular if supported by industry as well. This paper reports on such fruitful experiences at our universities through the math-analytical back-stepping and state-feedback control design methodologies. Computer simulation and laboratory experiments have demonstrated these controller designs possess quality performances, which are comparable with the other designs for the same applications.

Keywords: Advanced controls; back-stepping; control teaching; electrical power systems; graduate studies and research; power electronics.

1. INTRODUCTION

It is argued in here, the synergism of combined knowledge and technology transfer is most fruitful strategy supporting a fairly rapid but sustainable advancement of developing countries, in general, and enhancing their respective share in the market of automation and control products and services, in particular (Dinibütün and Dimirovski, 2004). Furthermore, due to the availability of computer networks and communication technologies and planned international co-operation, developing countries can achieve their fair share in intellectual services for automation and control (Dimirovski, 2004).

This paper validates the above argument through an analysis discussion of the authors' recent control results in applications to electrical power systems and power electronics (Li and co-authors, 2003; Li, 2003; Serafimovski, 2001; Serafimovski and Dimirovski, 2004) while teaching advanced courses on control to graduate students. To shed light on the aforementioned results, first the respective problems and background research are outlined in Section 2 Main results are given in Section 3. Conclusion and references follow thereafter.

2. TIMELY RESEARCH WHILE TEACHING ADVANCED CONTROLS

In modern electric power industry, power systems are characterized with the increasing complexity of configuration and therefore structured in areas operated by the respective control centres that ensure the requirements for steady-state stability of the overall system are maintained (Electric Power Research Institute, 1996 a). In addition to the operational security, there is ever increasing desire for augmented system utility capacity. However, the requirement that all voltages must stay within strict lower and upper limits under any sort of disturbances, representing a variety of technical constraints, is one of the three major operational requirements (e.g, see Wood and Wollenberg, 1996). For these reasons, modern electric power systems employ active electronic high-power control devices to create so called Flexible AC Transmission Systems (FACTS), and Thyristor Controlled Series Compensators (TCSCs) are typical FACTS devices (Electric Power Research Institute, 1996 b).

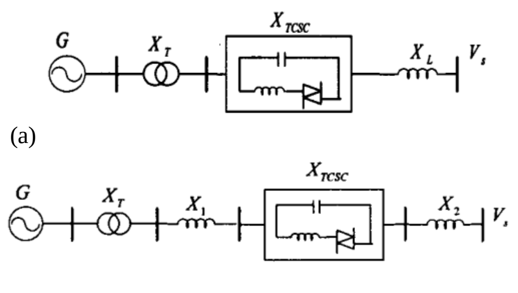


Fig. I. Model of a single-machine infinite-bus power system employing TCSC devices; (a) conceptual and (b) in more detail.

Thyristor controlled series compensator (see Figure I) can provide voltage support, reduce the equivalent electric distances in a economic and effective mode, improve the damping performance, facilitate the control of load flow, and enhance the stabilities of power systems with long transmission lines. Nonetheless, rather serious stability situations with regard to nonlinear dynamics al power system operation can occur prior to power system stabilizes in a steady state (Wildberger, 1994). Conventional linear stabilizers of TCSC cannot keep the system transient stability in the case where operational conditions and system parameters change significantly (Son and Park, 2000). They are suitable only for small disturbance about a steady state operation point (Zhou and Liang, 1999). The design synthesis based on feedback linearization using the differential geometric approach has the disadvantage in the fact that the parameters of the system have to be exactly (Gan and co-authors, 2000). Besides, the electromagnetic transient course of TCSC itself is not accounted for. The obtained controller is valid locally for the linearized system only, which is not guaranteed in increasingly de-regulated operation of electric power systems.

The back-stepping method of nonlinear control design (Krstic and co-authors, 1995) yields better designs because of both: the procedural concise design, and the validity in processing parameter uncertainty. In controller design solution by Shen and co-authors (1999), however, for the exciter systems using back-stepping with realistically assumed uncertainty in parameters the outcome was an uncontrollable system representation. It is therefore that, on the grounds of non-linear models with uncertainties (Electric Power Research Institute, 1996 a, b)

$$\begin{cases} \dot{d} = w - w_0, \\ \dot{w} = \dfrac{w_0}{H}\left(P_m - E_q' V_S\, y_{t\,\mathrm{csc}} \sin d - \dfrac{D}{w_0}(w - w_0) \right), \\ \dot{y}_{t\,\mathrm{csc}} = -\dfrac{1}{T_{t\,\mathrm{csc}}}\left(-y_{t\,\mathrm{csc}} + y_{t\,\mathrm{csc}\,0} + u\right), \end{cases} \quad (1)$$

two new back-stepping solutions have been derived and proved in (Li and co-authors, 2003; Li, 2003). These control designs guaranteed practical asymptotic stability of the single-machine-infinite-bus (SMIB) electrical power system employing TCSC (Figure I) regardless the disturbances and variations.

The other case study, while teaching advanced control theory, that yielded a novel control design and implementation (Serafimovski, 2001) is the voltage stabilization of buck-boost converter (BBC; Figure II) via state-feedback regulation using passivity technique (Sira-Remirez and co-authors, 1997). Plant is a switched-mode dc-dc converter that is inherently non-linear and variable-structure system because of elements such as diodes and switches (Bose 1997; Mohan and co-authors, 1995).

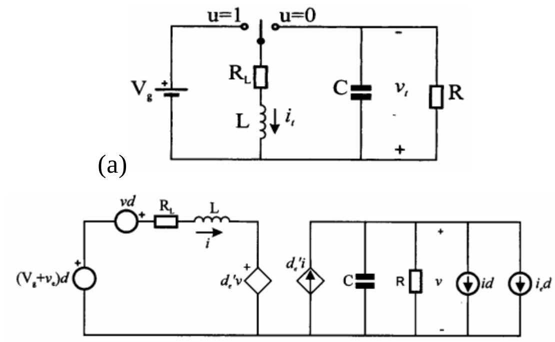


Fig. II. Schematic (a) and equivalent circuit (b) of a buck-bust converter (BBC) device.

They are operated by discrete control signal, which is obtained by modulation of the continuous control signal representing the control law, to make the topological structure of the converter vary with time (Bose, 1997). Although an inherently nonlinar system, linear continuous models were developed (e.g. Wester and Middlebrook, 1973) in order to appply feedback control theory to arrive at stable design of compensation network. Designs are valid so-called small-signal mode. If otherwise, a large-signal model is required for proper analysis and synthesis (e.g., Chen and Cai, 1990; Sira-Ramirez and co-authors, 1997). Based on a similar study for boost converter by Grasa (2000), Serafimovski (2001) carried out a large-signal design has been elaborated for the buck-boost topology.

The state equations with $x_t = \left[i_t \quad v_t \right]^T$, describing the behaviour of BBC during the switching period, when the switch is on (*k=1*) and when the switch is off (*k=2*), may be represented as follows:

$$\dot{x}_t(t) = A_k x_t(t) + b_k, \quad \text{k = 1,2} \qquad (2)$$

where

$$A_1 = \begin{bmatrix} -R_L/L & 0 \\ 0 & -1/RC \end{bmatrix}, \quad b_1 = \begin{bmatrix} V_g/L \\ 0 \end{bmatrix},$$

$$A_2 = \begin{bmatrix} -R_L/L & -1/L \\ 1/C & -1/RC \end{bmatrix}, \quad b_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Further, instead of two matrix equations, (1) can be expressed as follows

$$\dot{x}_t = (A_1 x_t + b_1)u + (A_2 x_t + b_2)(1-u)$$

or, equivalently:

$$\dot{x}_t = A_2 x_t + b_2 + (A_1 - A_2)x_t u + (b_1 - b_2)u. \quad (3)$$

Here, *u=1* when the switch is on, and *u=0* when it is off. A global stability condition was obtained (Serafimovski and Dimirovski, 2004) using passivity technique (Hill and Moylan, 1976; Sira-Ramirz, 1997), whereby the balance of absorbed and dissipated power in the two-port model of the regulator (Figure V) is properly examined. Experiments have validated wel computer simulation results.

3. DESIGN CASE STUDIES AND ACHIEVED CONTROL PERFORMANCES

In the sequel, the main points highlighting the novel results are presented and some discussion given. The simulation results showing the achieved control performance and demonstrating the advantages of the proposed designs are used.

3.1. Back-stepping Designs for TCSC Power System

As mentioned, two beck-stepping designs have been developed and their asymptotic stability proved. The first one was based on a simplified, second-order and one for the other a third-order non-linear model non-linear model of the plant dynamics (Li and co-authors, 2003), the solution for which is briefly presented below.

In system (1), variables and other physical quantities are known to have the following meanings: d is the rotor angle of the generator; w is the relative speed of the generator; P_m is the mechanical input power of the generator, which is assumed as constant; D is the per unit damping coefficient constant; H is the constant inertia; E'_q is the transient EMF in the quadratic axis of the generator, which is assumed as constant; V_S is the infinite bus voltage; $y_{t\,csc} = 1/(X'_{d\Sigma} + X_{t\,csc})$ is the impedance of the whole system; $X_{t\,csc}$ is the equivalent reactance of TCSC in p. u.; $X'_{d\Sigma}$ is the external reactance; and u is the control input. It should be noted that model (1) is an essentially non-linear system in all respects.

System (1) is readily transformed into a state-space representation model

$$\dot{x}_1 = x_2, \qquad (4\,a)$$

$$\dot{x}_2 = -\frac{D}{H}x_2 + \frac{w_0}{H}\cdot[P_m - \\ - E'V_E(x_3 + y_{t\,csc0})\sin(x_1 + d_0)], \quad (4\,b)$$

$$\dot{x}_3 = \frac{1}{T_{t\,csc}}(-x_3 + u), \qquad (4\,c)$$

which is appropriate for the back-stepping design, by defining states: $x_1 = d - d_0$, $x_2 = w - w_0$, $x_3 = y_{t\,csc} - y_{t\,csc\,0}$, where d_0, w_0, $y_{t\,csc\,0}$ are the initial values of corresponding variables. It is physically justified that $k_1 = \frac{w_0}{H}$, $k_2 = \frac{w_0 E'_q V_S}{H}$ are known. However constant $q = -\frac{D}{H}$ has to be assumed unknown, possibly with uncertainty, because of parameter D, and this is to be accounted for in the control design. Following the practice of electrical power systems, disturbance vector $w = [w_1 \quad w_2]^T$ can be assumed with w_1, w_2 unknown functions in L_2 space. System (4) is then transformed to:

$$\dot{x}_1 = x_2, \qquad (5\,a)$$

$$\dot{x}_1 = q\,x_2 + k_1 P_m \\ - k_2(x_3 + y_{t\,csc0})\sin(d_0 + x_1) + w_1, \quad (5\,b)$$

$$\dot{x}_3 = \frac{1}{T_{t\,csc}}(-x_3 + u) + w_2, \qquad (5\,c)$$

$$z = \begin{bmatrix} q_1 x_1 \\ q_2 x_2 \end{bmatrix}, \qquad (6)$$

with $z = [q_1 x_1 \quad q_2 x_2]^T$ representing the regulated output. Quantities q_1 and q_2 are nonnegative weighted coefficients, representing the weighted proportion of state variables x_1 and x_2 into the system output, which are to be determined by the designer in each particular case study. For system (5)-(6) with uncertainty parameter and external disturbances, adaptive back-stepping method can be applied to design nonlinear robust (steam-valve) controller.

First, it should be noted the design procedure can be transformed into the dissipative system problem through constructing storage function $V(x)$ such that the system is satisfying the supply rates $S = g^2\|e\|^2 - \|z\|^2$. That is, the following dissipativity inequality holds for any final time $T > 0$:

$$V(x(t)) - V(x(0)) \le \int_0^T \left(g^2\|e\|^2 - \|z\|^2\right)dt. \qquad (7)$$

Then the L_2 gain from the disturbance to the output of the system is smaller than or equal to g . Then a lengthy derivation yields the feedback control law

$$u = x_3 + T_{t\csc} \cdot$$
$$\left(\frac{1}{k_2} \left(\frac{m_1 x_2 + (m_2 + \hat{q})(\hat{q} x_2 + k_1 P_m - k_2 (x_3 + y_{t\csc 0}) \sin(d_0 + x_1)) + \dot{\hat{q}} x_2}{n_1} - \frac{(m_1 x_1 + m_2 x_2 + \hat{q} x_2 + k_1 P_m) x_2 n_2}{n_1^2} \right) - \left(\frac{m_2 + \hat{q}}{k_2 n_1 g} \right)^2 e_3 - \frac{e_3}{g^2} \right) \quad (8a)$$

and the parameter update law

$$\dot{\hat{q}} = -\dot{\tilde{q}} = r \left(e_2 - \frac{(m_2 + \hat{q}) e_3}{k_2 n_1} \right) x_2 . \quad (8b)$$

Finally, it can be shown that

$$\dot{V}(x) \le g^2 \|w\|^2 - \|z\|^2 , \quad (9)$$

and by integrating both sides of inequality (9) the dissipative inequality (7) is readily obtained. Hence, from the disturbance to the output, the system posses a L_2 gain. The closed–loop error dynamics

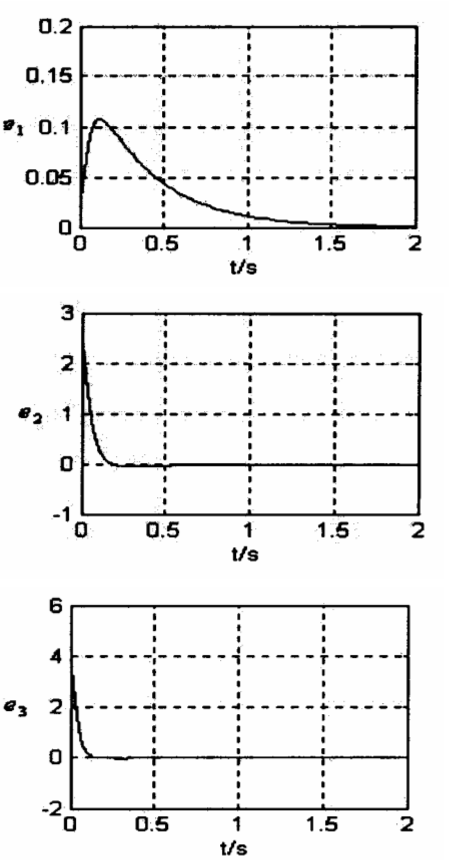
$$\begin{cases} \dot{e}_1 = e_2 - c_1 e_1 \\ \dot{e}_2 = -\left(\frac{1}{g^2} + \frac{1}{2} q_2^2 \right) e_2 + (c_1 q_2^2 - s) e_1 + \tilde{q} x_2 \\ \dot{e}_3 = -\left(\left(\frac{m_2 + \hat{q}}{k_2 n_{11} g} \right)^2 + \frac{1}{g^2} \right) e_3 + \tilde{q} \frac{(m_2 + \hat{q}) x_2}{k_2 n_1 f} \end{cases} \quad (10)$$

under the control law (8) is guaranteed to be asymptotically stable: when $w = 0$, then $e_1 \to 0$, $e_2 \to 0$, $e_3 \to 0$ as $t \to \infty$. From the very definitions of x_1, x_2, x_3 (and x_2^*, x_3^*, respectively), it follows at once that x_1, x_2, x_3 will also converge to zero, thus the practical stability is achieved.

The resulting control design has been examined via computer simulations of the example with data given in the literature (Son and Park, 2000). In particular, for the error system dynamics these simulation results are shown in Figure III, and Figure IV depicts the convergent evolution of adaptation of the uncertain parameter in the closed-loop operation of the designed control. It is apparent from Figure IV that the update of parameter estimation variable converges rather quickly to real-world value of the parameter q . The similar fast convergence in eliminating dynamic errors can be inferred from Figure III

3.2. Passivity Design Technique for BBC Device

The novel passivity-technique based control design for a buck-boost dc-dc converter (BBC device; see Figure II) has been developed in (Serafimovski, 2001) and further studied and asymptotic stability proved (Serafimovski and Dimirovski, 2004).



(a)

(b)

(c)

Fig. III. Response curves of the system error dynamics.

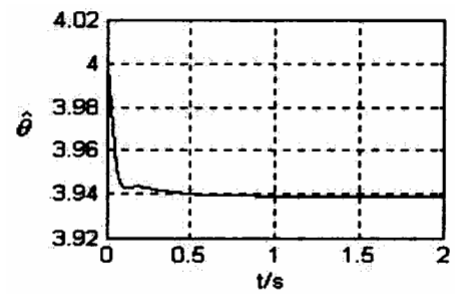


Fig. IV. Response curve of the update of parameter estimation variable.

The switching frequency is chosen significantly higher than the converter natural frequencies, of course. Hence discontinuous control signal u can be approximated by a continuous function d_t that designates the converter duty cycle with a range of values in the interval [0, 1]. In turn, the simplification of model (3) leads to the averaged model

$$\dot{x}_t = A_2 x_t + (A_1 - A_2) x_t u + b_1 u . \quad (11)$$

System (11) is a bilinear representation of the operating process of buck-boost converters (BBC devices). At the operating equilibrium, state variables and duty cycle are sums of the value in the equilibrium point and the perturbed values

$$x_t = x_e + x\,,\;\; d_t = d_e + d\,. \qquad (12)$$

Hence, it follows

$$\left(\dot{x}_e + \dot{x}\right) = A_2\left(x_e + x\right) + \left(A_1 - A_2\right)\cdot \cdot\left(x_e + x\right)\left(d_e + d\right) + b_1\left(d_e + d\right) \qquad (13)$$

Separating the equilibrium point determination and the dynamic analysis gives

$$x_e = \begin{bmatrix} i_e \\ v_e \end{bmatrix} = \begin{bmatrix} \dfrac{V_g d_e}{R_L + (1-d_e)^2 R} \\ \dfrac{V_g d_e (1-d_e) R}{R_L + (1-d_e)^2 R} \end{bmatrix}, \qquad (14)$$

$$\dot{x} = Ax + Bxd + bd\,, \qquad (15)$$

where:

$$A = A_2 + (A_1 - A_2)d_e = \begin{bmatrix} -R_L/L & -d_e{}'/L \\ d_e{}'/C & -1/RC \end{bmatrix},$$

$$B = A_1 - A_2 = \begin{bmatrix} 0 & 1/L \\ -1/C & 0 \end{bmatrix},$$

$$(16)$$

$$b = (A_1 - A_2)x_e + B_1 = \begin{bmatrix} (V_g + v_e)/L \\ -i_e/C \end{bmatrix},$$

$$d_e{}' = 1 - d_e\,.$$

Hence, the system dynamics can be described by

$$L\frac{\partial i}{\partial t} = -R_L i - d_e{}' v + vd + (V_g + v_e)d\,, \qquad (17)$$

$$C\frac{\partial v}{\partial t} = d_e{}' i - \frac{v}{R} - id - i_e d\,. \qquad (18)$$

These equations describe the incremental variable relationships. Then the large-signal stability of BBC and respective equilibrium conditions can be estabilhed (Serafimovski and Dimirovski 2004).

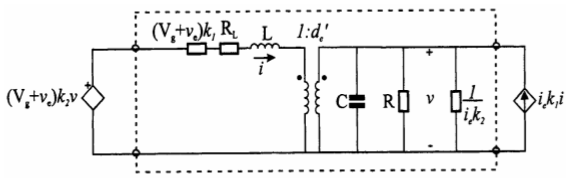


Fig. V. Two-port representation of the switching circuit regulator.

In particular, the application of passivity technique has shown that control law for BBC can be designed as a special linear combination of the state variables. Once large-signal stability is guaranteed, the design of desired dynamics and robustness of the switching regulator can be designed rigorously.

In turn, this design can be carried out using the BBC incremental model

$$\begin{bmatrix} \dot{i} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} -R_L/L & -d_e{}'/L \\ d_e{}'/C & -1/RC \end{bmatrix}\begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} (V_g + v_e)/L \\ -i_e/C \end{bmatrix} d$$

$$(19)$$

And, for the control law

$$d = -a_{\max}\left((V_g + v_e)i - i_e v\right), \qquad (20)$$

the loop gain is found to be

$$T(s) = -a_{\max}\left(v_e\frac{I(s)}{D(s)} - i_e\frac{V(s)}{D(s)}\right) =$$

$$-a_{\max}\frac{\left(\dfrac{v_e(V_g + v_e)}{L} + \dfrac{i_e^2}{C}\right)s + \dfrac{1}{LC}\left(\dfrac{v_e(V_g + v_e)}{R} + R_L i_e^2 - d_e' V_g i_e\right)}{s^2 + \left(\dfrac{R_L}{L} + \dfrac{1}{RC}\right)s + \dfrac{1}{LC}\left(\dfrac{R_L}{R} + d_e'^2\right)}$$

$$(21)$$

Here, the gain coefficient $a_{\max}$ is obtained by a special analysis of the BBC physics (Serafimovski, 2001). In particular, for BBC device with the parameter values *L=200 mH, R_L=200 mW, C=200 mF, R=10 W, V_g=12 V, T_s=20 ms*, d_e=*0.525* and the equilibrium point v_e=*12.18 V and* i_e=*2.6 A*, the gain coefficient was found $a_{\max}$ $=2\times10^{-3}$. For the value of $\alpha_{\max}$, the closed loop transfer function has two equal real eigenvalues at -2.56×10^{-3}.

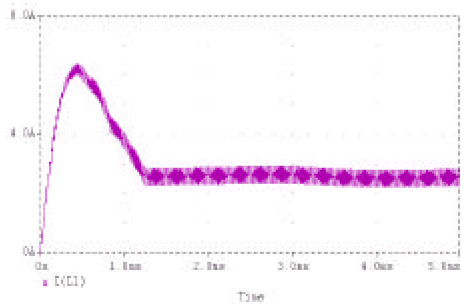


Fig. VI. Inductor current response during start-up from zero initial conditions.

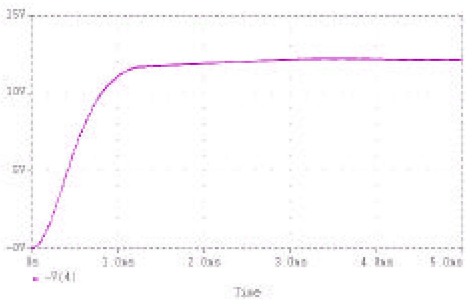


Fig. VII. Inverted capacitor voltage response during start-up from zero initial conditions.

Then both physical experiments and simulations of BBC device for these values have demonstrated high-quality performance. Figures VI and VII show sample of experimentally validated design results for the above specified BBC device and the derived control law (20)-(21) with the value for the gain coefficient a_{max} =2·10^{-3}. The quality performance may well be inferred form these figures.

4. CONCLUSION

The two cases of knowledge, not solely technology, transfer are reported that have been experienced recently in the biggest and in one of rather small developing country. Novel control designs for electrical power systems, employing thyristor controlled series compensation, and for autonomous power systems, employing power-electronic buck-boos dc-dc converter, have been elaborated. These clearly demonstrate the knowledge transfer is more important and vital, and may be achieved via carefully tailored graduate studies that include combined basic and advanced control theory. In turn, these courses enhance both academic and applied research, and contribute to combined knowledge and technology transfer.

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