Electric Power Systems Research 81 (2011) 2188–2197

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Optimal tuning of linear controllers for power electronics/power systems applications

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ARTICLE INFO

Article history:
Received 30 May 2011
Received in revised form 1 August 2011
Accepted 2 August 2011
Available online 3 September 2011

Keywords:
Linear controllers
Tuning
Optimal control
UPS inverter
Distributed generation

ABSTRACT

This paper presents a new method for tuning various linear controllers such as Proportional–Integral (PI), Proportional–Integral–Derivative (PID) and Proportional–Resonant (PR) structures which are frequently used in power electronics and power system applications. The linear controllers maintain a general structure defined by the Internal Model Principle (IMP) of control theory. The proposed method in this paper is twofold. The first perspective uses the well-known concept of the Linear Quadratic Regulator (LQR) to address the problem as a regulation problem. The *Q* matrix of the LQR design is then finely adjusted in order to assure the desired transient response for the system. The second perspective redefines the LQR in order to add capability to address the optimal tracking problem and is then generalized to systems with more than two states. These methods are then applied to two specific examples, one in an uninterruptible power supply (UPS) inverter system and the other one in a distributed generation (DG) system. In these examples, the tuning of PR and PI controllers is studied in great detail. These proposed design methods provide an easy and algorithmic procedure without jeopardizing stability or robustness. These tuning methods can also be utilized for linear state-space realization of any power converters. Both examples are supported via simulation and the results, which confirm analytical derivations, are presented and discussed.

1. Introduction

Power electronics and power system applications use various forms of linear controllers such as Proportional–Integral (PI), Proportional–Integral–Derivative (PID) and Proportional–Resonant (PR) controllers, to achieve control objectives mainly specified by the desirable transient and steady-state requirements. Such structures originate from the Internal Model Principle (IMP) of control theory, which states that a model of the desired commands (and disturbances) must exist in the loop to ensure desired steady-state operation and provide that the loop is stable [1]. Thus, a PI (or PID) controller is appropriate for step references and a PR controller for sinusoidal references. The IMP, however, only guarantees the steady-state performance (given that the loop is already stable). The transient response must be controlled by appropriate selection of the controller gains.

There is an abundance of applications for PI, PID and PR controllers in power systems and power electronics systems. Some examples are given below without discussing the details for brevity. In [2], an advanced method is proposed for tuning a PID controller in a hydro-turbine for speed and active power control. PI and PR controllers are used in [3] for parallel and series inverters in a micro-grid power quality compensator. Note that the gains are tuned analytically based on the concepts of phase and gain margins. This concept is developed for a PR controller in [4] for output voltage control of parallel uninterruptible power supplies (UPS). Using a Proportional–Integral-Resonant (PI-RES) for multiple harmonic controls in a Distributed Generation (DG) unit is proposed in [5]. In addition, PR controllers in the stationary reference frame are designed for the series and parallel grid-side converters in a grid connected doubly-fed induction generator (DFIG) wind turbine yielding better dynamic performance during network unbalances [6]. The frequency injection method for tuning of a PID controller in switch mode power supplies is discussed in [7]. PI and PR controllers are also used and analytically tuned for an inverter-based DG unit [8] and also in a multilevel active filter [9]. In [10], a fuzzy-based self-tuning PI is proposed for a thyristor-controlled series capacitor (TCSC) system to improve power system stability. Evolutionary-type algorithms are also used to adjust the fuzzy PID controller gains for an automatic voltage regulator (AVR) [11]. Model predictive control (MPC) is used in [12] to provide on adaptive under-voltage load shedding scheme to protect power systems

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doi:10.1016/j.epsr.2011.08.001

against voltage instability. Tuning a PID controller using the LQR method for a multivariable system is presented in [13]. The LQR in [14] adjusts the gains in a multi-loop scheme control of a UPS output voltage. That scheme is however dependent on the output LC-filter parameters and also requires the measurement of the load current. Similar optimal control with LQR can be found in [15] where a real-time emulation is required for loading in a voltage source inverter (VSI). The LQR technique is additionally used in [16] to adjust a multi-loop scheme which is based on a PI controller and the time-derivative of the reference signal in a set of parallel inverters. The work in [17] also uses the LQR technique in combination with dead-beat control to improve the damping of an LCL-filter used to connect a three-phase source to the grid. A nonlinear control of a linearized wind turbine power generation with DFIG is optimized by LQR in [18]. Feedback linearization controls a VSI using pole placement technique to achieve controller coefficients [19].

The well-known and popular concept of LQR offers a highly advantageous method for optimally tuning controller gains in a feedback system; such a method provides appropriate phase-gain margin and variation with respect to nonlinearities [20]. Furthermore, the robustness of a loop can be represented by an interrelation of robust and optimal controllers [21–23]. LQR design can offer high robustness in the subject of system parameter uncertainties, resulting in 60° of phase and infinite gain margins [24]. To apply this method to a regular loop with output feedback, however, the system equations must be put into a state-feedback form. This means that an output feedback controller may or may not be expressible in LQR formulation. The second limitation is that the LQR addresses a regulation problem and cannot originally be applied to a tracking problem, which is desired in practice. These two drawbacks have often been considered as hurdles when working with LQR and have not been systematically addressed in the literature. In this paper, the objective is to overcome these two drawbacks of the LQR method. We are particularly concerned about power system applications, an UPS and a DG system are specific examples addressed in this work.

The proposed technique of this paper is twofold. The first fold finds an optimal Q matrix (in the LQR formulation) which ensures the desired transient response characteristics. This is performed based on the concept of dominant closed-loop poles by mathematically reversing the procedure in the LQR concept formulation. The second approach is based on reformulating and modifying the LQR problem such that optimal tracking is also addressed, i.e. incorporating a “tracking-based” control scheme. The power converters can also employ these tuning methods for their linear state-space realization.

The structure of the paper is as follows. A review of the LQR concept is presented in Section 2. Descriptions of a UPS inverter system and a DG unit as case-study systems are provided in Section 3. Section 4 designs optimal feedback controllers for the case-study systems by optimally tuning the Q matrix based on the concept of dominant poles. An alternative design approach, which directly addresses the tracking problem, is presented in Section 5. It is applied to the UPS and DG unit examples and is generalized to systems with more than two states. Realistic simulation results in PSCAD are presented in Section 6 to verify the analytical results. Section 7 concludes the paper.

2. LQR concept

A linear time-invariant system can generally be described by the following state-space representation

$$\begin{aligned} \dot{x} &= Ax + Bu \quad t > 0 \quad x(0) = x_0 \\ y &= Cx + Du \quad t \geq 0 \end{aligned} \tag{1}$$

where $A \in \Re^{(n\times n)}$, $B \in \Re^{(n\times m)}$, $C \in \Re^{(p\times n)}$, $D \in \Re^{(p\times m)}$ are constant matrices, u is the control signal, x is the state vector, and y is the system output.

The conventional LQR problem is to design a full-state feedback law $u = -Kx$ optimally regulate the states and its output to zero [20]. In the LQR problem, the optimality is measured by

$$J(u) = \int_0^{\infty} (x^T Q x + u^T R u) dt \tag{2}$$

where $Q = Q^T \in \Re^{(p\times p)}$ is a positive (semi) definite and $R = R^T \in \Re^{(m\times m)}$ is a positive definite matrix. It is shown that the optimal K is given by

$$K = R^{-1} B^T F \tag{3}$$

where the symmetric matrix $F = F^T \in \Re^{(n\times n)}$ is obtained from the Algebraic Riccati Equation (ARE), i.e.

$$A^T F + FA + Q - FBR^{-1} B^T F = 0 \tag{4}$$

The closed-loop dynamics under state feedback law with $u = -Kx$ given by

$$\dot{x} = (A - BK)x = A_{CL} x \tag{5}$$

and the eigenvalues of A_{CL} are the closed-loop poles.

Existence of the solution is under the assumptions that (A,B) is stabilizable, (A,C) detectable, $R > 0$, $Q \geq 0$ and (Q,A) has no unobservable mode on the imaginary axis [20,25]. In addition, R can be chosen unit without lose of generality.

For every given Q matrix, the closed-loop poles are optimally assigned by the LQR solution to achieve optimal regulation. In practice, however, we desire the control system output to track some specific reference command such as a step or a sinusoid. This often requires the addition of another output feedback controller in addition to the state-feedback. Unfortunately, the LQR approach cannot be directly used to optimally design every gain, including those of the state-feedback and of the output feedback. Thus, to overcome this drawback of the method, we propose two methods in this paper. The first method adjusts Q matrix in order to place the closed-loop poles within a specific set in the complex plane which ensures desired tracking (or transient) characteristics. The second method directly addresses the tracking problem.

3. Review of UPS and DG control systems

To develop the proposed optimal tuning method, two specific applications of the method are exemplified. One is a single phase UPS system and the second a dq -transformed three phase grid-connected DG system. For both systems, it is shown that the proposed optimal tuning method is successively applied to PR and PI controllers. In this regard, these two systems are described briefly in this section.

3.1. UPS inverter system

Fig. 1 shows the power stage of a single-phase inverter which includes an IGBT half-bridge configuration and an LC-filter. The equivalent series resistance of the filter capacitor is not considered in the model since its effect appears far above the frequency range of concern [26]. The differential equations that describe the large-signal dynamic behavior of this converter are

$$L\frac{di_L}{dt} = \frac{V_{in}}{2} u - v_o - r_L i_L \tag{6}$$

$$i_C = C\frac{dv_o}{dt} = i_L - i_o \tag{7}$$