A Design Approach For Digital Controllers Using Reconfigurable Network-Based Measurements

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Abstract—In this paper, the authors propose and analyze a network-based control architecture for power-electronics-building-block-based converters. The objective of the proposed approach is to distribute the control system to guarantee maximum flexibility in the control of power distribution. In the proposed control system, controller and controlled devices are connected through the network, which affects the measurement and control signals mostly due to delays. The main goal of this work is to outline a design methodology for controllers operating with measurements coming from a network. The approach proposed here assesses the robustness of the control system in the presence of delay and aims to design an optimal controller for robustness against network delays. This methodology is based on uncertainty analysis and assumes that the delays are the main element of uncertainty in the system. The theoretical foundations of this approach are discussed, together with the simulation and implementation of a physical laboratory prototype.

Index Terms—Induction machines, networks, power systems measurements, robustness, uncertainty.

I. INTRODUCTION

RECENTLY, the power electronics building block (PEBB) concept has widely been accepted, and commercial PEBB devices have been implemented in many applications and fields. A very important application is given by the interface converters used in power distribution systems. One example of such power distribution system is the future All Electrical Ship [1].

To dynamically manage such power system, a flexible, reliable, and integrated control system needs to be built. In ship power system applications, it is extremely critical to design the control system in such a way as to ensure safe operating modes both under normal or emergency conditions (e.g., partially damaged system). To achieve this goal, the PEBBs play an important role by offering a high degree of flexibility in the management of the power flows.

In this paper, the authors propose and analyze a network-based control architecture for PEBB devices. The objective of this approach to PEBB control is to create a distributed control system that is capable of guaranteeing maximum flexibility in the control of a power distribution system. In particular, the networked controllers are seen as distributed control resources that can be allocated, at any given time, for the control of a specific piece of hardware (PEBB converters in particular) and for specific functionalities (e.g., feeding loads, charging energy storages, and correcting power quality). In this architecture, controller and controlled device communicate through the network, which affects the measurement and control signals mostly with stochastic delays.

The coordination and reconfiguration of controller deployment are done through an agent-based system at system level. Such intelligent system is able to reconfigure the control architecture assigning controllers and functionalities to the PEBBs, depending on the overall mission of the system and on the specific occurrence. The analysis of the agent system is not the focus of this work, but the underlying approach has been presented in [2]. The main goal of the work discussed here is to outline a design methodology for controllers operating with measurements remotely taken and transmitted over the network.

An approach is proposed to assess the robustness of the control system in the presence of delays and to design for robustness to network delay. This approach is based on uncertainty analysis, assuming that delays are the main element of uncertainty in the system. The theoretical foundations of this approach are discussed, together with the simulation and implementation of a physical laboratory prototype.

Preliminary results of this study have been presented in [3]. In this paper, the work is extended, providing a design methodology and experimental validation. In particular, the field-oriented control on an induction machine is adopted as a case study to demonstrate the proposed design procedure. The speed-loop control is realized by a network-based optimal proportional–integral (PI) controller. The design is performed by treating the delays as main uncertainties. Polynomial Chaos Theory (PCT) is adopted as theoretical basis for design of the optimal controller and the assessment of its robustness.

II. NETWORK-BASED CONTROL

The idea of performing closed-loop control through the network is not new [3]. Nonetheless, applications in the power electronics domain are still limited. An overview of the topic is provided in [4]. Predictive controllers are often used to address the issue of network delay; in particular, [5] focuses on the case of delay on the feedback line, [6] on the case of forward line delay, and [7] on the case where the delay is directly assessed.

Huang and Nguang [8] proposed a solution of the stabilization problem for state-feedback uncertain networked control
systems with random communication time delays. An approach with neural network delay compensator and fuzzy PID controller is presented in [9], together with experimental results. An implementation specifically for power electronics applications is presented in [10] for stepping motors, although in an open loop.

The motivations for a reconfigurable network solution for the control of power electronics systems have been provided in [11], where the architecture schematically shown in Fig. 1 is introduced and discussed. The main goal is to achieve a higher system reconfigurability leveraging on the feature that each controller can be allocated to any of the hardware devices at any time. This advantage is partially counterbalanced by the loss of bandwidth capability due to delays introduced by the network in the feedback measurement from the device to the controller and in the control signal from the controller to the device. The decision on the controllers’ deployment and the control strategy for mission consistency is taken at the upper level by a multiagent system.

The main challenges of designing the network-based controller addressed here are stability and robustness under the following effects due to the network:

1) random delay in the feedback loop carrying the measurement from the field device to the controller;
2) random delay in the forward loop taking the control signal from the controller to the field device;
3) variations in the rate of execution of the controller that may be not constant over time but may be affected by the delay action.

In literature, the majority of research focuses on the design of PI controllers, optimized for this new scenario. The typical solution adopted for this type of controllers is gain scheduling [12], [13]. A discussion on the issues related to multirate operation can be found in [14].

In this paper, the authors propose to model the effect of network delay as uncertainty by adopting a PC expansion of the model of the system [15], [16]. A preliminary application of this modeling approach to the control of power electronics systems is presented in [17], whereas a more advanced control approach is discussed in [18]. Here, the PC approach is extended to different control structures, and the mathematical conditions for robust stability are discussed.

The proposed procedure can easily be implemented with standard mathematical tools such as Matlab and Maple, thus making the process applicable to real systems with reasonable effort.

III. MATHEMATICAL FORMULATION OF THE PROBLEM AND DESIGN PROCEDURE

The linear system under analysis is summarized in block diagram form in Fig. 2.

The system in Fig. 2 can be modeled with a set of state equations. If we consider the network delay as an uncertain parameter with known probability density function (pdf), the model becomes a stochastic process. A truncated PC expansion can be applied to all the state equations, thus resulting in a deterministic model with an extended set of states. These new states are the coefficients of the truncated PC expansion of the original state variables. This transformation process can easily be automated with the help of Maple scripts [19]. Once the PC model is synthesized, the control design can be performed by solving a constrained optimization problem, where two conditions hold.

1) The cost function is designed to significantly penalize the uncertainty of the state variables, which, in mathematical terms, implies penalizing the coefficients of the PC expansion of the state variables representing other values than expected.
2) Constraints are added to enforce the control solution to be compliant with a specific control architecture (e.g., state space feedback or PI).

Different optimization functions can be adopted to perform the design. In the following, an example of application is proposed where an integral square error (ISE) optimal [20] method is adopted to design a PI controller.

The solution of the minimization problem yields the parameters of the controller, whose architecture is implicitly defined as the state equations of the closed loop.

IV. STABILITY ANALYSIS

Once the optimization problem is solved and the controller is fully defined, it is then important to verify that the resulting control system is stable for any possible value of delay, within the
The design objective is, in fact, to achieve a robust controller without the online adaptation of the parameters. This approach is similar to other methods for robust control design synthesis, as in [19]. The uniqueness of this approach, however, lies with the accounting of the whole pdf of the uncertain delay parameter. This approach is expected to yield a less conservative design with a computable risk factor associated to it.

The analysis of robustness is based on the analysis of convergence of the PC series expansion of the states. If the series actually converges, then the moments of the pdf of the state variables are finite. This is a necessary condition to guarantee the stability according to a bounded-input–bounded-output (BIBO) stability definition.

The proof of convergence can be obtained from the asymptotic convergence of the error of the expected value of the state variables, depending on the order of truncation. In other words, the exponential convergence to zero of the error of the expected value obtained from successive incrementally higher orders of truncation guarantees that the pdfs of the state variables converge to the correct one and that the moments are finite.

More formally, the procedure for robust stability verification can be described as in the following. Let us consider a linear system in the form:

\[ \dot{x} = Ax + Bu. \]  

(1)

Notice that matrix A in this case contains parameters of the system, as well as the delays.

Let us suppose that the system is affected by parametric uncertainty; in particular, the delay parameter is uncertain. This implies that a set of elements of matrix A is uncertain, with known pdf. As a consequence, the generic coefficient \( a_{ij} \) of matrix A can be expressed in terms of PC expansion [15], [16], i.e., as a function of a vector of random variables \( \xi \)

\[ a_{ij} = \sum_{k=0}^{\infty} a_{ij}^k \Phi_k(\xi). \]  

(2)
Let us also suppose that all these system uncertainties are defined over a closed and limited range. For example, we could assume that all the parameters have a uniform distribution, a Gaussian distribution, or other distributions. In any case, the analysis is limited to a finite subset of the support of the distribution with a predefined coverage factor.

For what concerns the definition of stability, the BIBO definition is adopted, implying that a stable system responds to a bounded input signal with a bounded output signal. If the system is stable for every possible value of the uncertain parameters, the whole set of possible transient responses is composed of bounded functions. In addition, if the system is stable and the transients are bounded, then all the moments of the pdf of a generic variable of the system are also bounded. Therefore, it can be stated that the PC expansion of the solution exponentially converges to the exact solution [16].

Let us now consider the expansion of system (1) with a PC expansion truncated at an order equal to $k$ and consider the application of a bounded input for the duration of a generic interval $0-t$. The coefficients of the expansion and, in particular, the zeroth-order coefficients of all the state variables are functions of time, and their 2-norm can be computed. Let us call $x_{0k}$ the zeroth-order coefficient of state variable $x$ when the polynomial expansion is truncated to order $k$. The 2-norm is defined as

$$\|x_{0k}\|_2^2 = \int_0^t x_{0k}^2(\tau) d\tau. \quad (3)$$

The value of the zeroth-order coefficient also depends on order $k$ of the expansion. Thus, there is a difference between the expected value at orders $k$ and $k+1$ of the expansion, and this represents the error due to the truncation of the expansion at order $k$ due to a one-order difference.

Naming $x_{i0k}$, which is the zeroth-order coefficient of the $i$th state variable expanded to order $k$, we can then introduce the norm of the state of the system $\|X_{0k}\|^2$ in the form

$$\|X_{0k}\|^2 = \sum_{i=1}^n \|x_{i0k}\|^2. \quad (4)$$

This value is the sum of the squares of all the norms of the state variables of the system.

If the system is stable, the norm $\|X_{0k}\|$ converges to its correct value. As a result, the following condition holds:

$$\lim_{k \to \infty} \left( \|X_{0k}\|^2 - \|X_{0(k+1)}\|^2 \right) = 0. \quad (5)$$

The same should occur for all the coefficients and, for example, for the first-order term

$$\lim_{k \to \infty} \left( \|X_{1k}\|^2 - \|X_{1(k+1)}\|^2 \right) = 0. \quad (6)$$

As a result, for a system expanded to the first order, if (5) and (6) hold, the necessary condition for robust stability can be inferred.

V. EXPERIMENTAL ACTIVITY

Let us now apply the approach to the control system of an induction machine. The control method of choice for the induction machine is field-oriented control [21], and its current-loop control runs locally (PEBB’s site) without the effect of network delay. The speed-loop control runs on a remote PC, and the values it exchanges with the controlled system are affected by network delays. The control structure is shown in Fig. 3.
In this section, the stochastic characteristic of the network delay is studied first. Second, a PC expansion model considering the two uncertainties is obtained. Third, an optimal PI controller is designed to minimize the error between reference and the system’s output. Fourth, stability analysis based the proposed method is verified. Fifth, the simulation result in Simulink is presented. Finally, the experiment results are presented. The same designed PI controller remotely and locally runs, and their control performances are compared.

Following this design procedure, one can design a network-based controller for other devices, such as voltage-loop control of dc–dc converters, as far as the required control bandwidth falls in limited range. This design procedure also provides an analytical way to design a robust controller for the systems with multi-uncertainties.

**A. Delay Study**

To get proper PC expansion model, the stochastic characteristic of network delay is studied first. Two PCs (A and B) use a Transmission Control Protocol (TCP)/Internet Protocol socket to set up the communication. For every test loop, a message called M is sent out by B to A, whereas A returns the same M back to B immediately after receiving it. When B gets M back, it records the time delay in the loop. Basically, A functions as an echo server. The time costs for each way (from A to B and from B to A) are assumed to be equal. The cable length between the two PCs is 20 ft, and a switch is used to bridge the PCs together. The delay measured in this test includes the transmission delay on cable and switch and the time cost for software execution. Test results amounting to 4900 are recorded, and the mean value and variance of one-way delays are 0.0078 and 0.000822 s, respectively. The probability distribution of 4900 tests, in Fig. 4, can be approximated with a Gaussian distribution. The PC form of the system is obtained, starting from a fourth-order representation with two uncertain parameters. The state-space matrices (A, B, C, and D) of the fourth-order model are first obtained: starting from these matrices, the first-order PC expansion matrices (A_pct, B_pct, C_pct, and D_pct) are evaluated. The dimension of A_pct results is 12 × 12. The flowchart of the PC expansion procedure is shown in Fig. 5. The complete Maple script cannot be reported in this paper for lack of space, but it can be obtained by request to the authors of this paper.

**C. Optimal Control Design**

In this experiment, an ISE optimal [20] method is adopted to design an optimal PI controller. The control target is to minimize the error between the reference r(t) and the system output y (Fig. 3).

In (7), y comes from the PC first-order expansion model in (8). In (8), G_pct stands for the closed-loop transfer function of the PC first-order expansion model

\[
\text{ISE}_{\text{min}} = \min \int_{0}^{\infty} |y(t) - r(t)|^2 \, dt
\]

\[= \min \left( \frac{1}{2\pi} \int_{-\infty}^{\infty} |Y(j\omega) - R(j\omega)|^2 \, d\omega \right)\]

\[
\text{ISE}_{\text{min}} = \min \int_{0}^{\infty} |y(t) - r(t)|^2 \, dt
\]

\[G_{\text{pct}} = C_{\text{pct}} (sI - A_{\text{pct}}) B_{\text{pct}} + D_{\text{pct}}\]

\[Y(s) = G_{\text{pct}} \cdot R(s)\]

\[G_{\text{pct}}(sI - A_{\text{pct}}) B_{\text{pct}} + D_{\text{pct}}\]

\[Y(s) = G_{\text{pct}} \cdot R(s)\]

The \(K_p\) and \(K_i\), which minimize (7), are 0.34 and 0.01, respectively. \(\text{ISE}_{\text{min}}\) is 0.1553.

**D. Stability Analysis**

The parameters used for the simulation test are reported in Table I, with the \(K_p\) and \(K_i\) obtained in previous section. Under these conditions, the system’s step response is shown in Fig. 6. The error norm and the log of the error norm series, as shown in Fig. 7, quickly converge toward zero, thus indicating that the
Fig. 10. Whole system schematic in Simulink.

Fig. 11. Control schematic.

system is robust stable. In this case, the PC expansion of the whole model is up to the fourth order (Table II).

Increasing the uncertainty’s variance up to 2.8 ms\(^2\), the system becomes unstable, and the zeroth order does not converge. In this situation, the PCT expansion model does not converge, and then, the modes of the pdf of the variables are unbounded. Therefore, as expected, the error series no longer converges, as shown in Figs. 8 and 9. In both cases, the PC expansion of the whole model is up to the fourth order.

E. Simulation in Matlab

The system is first tested in the Simulink environment. In this simulation, the induction motor, power supply, and PEBB are represented by the corresponding models in Simulink’s Simpower System toolbox, and the nonlinear characteristics of these components are included. The scheme of the whole system is shown in Fig. 10. Fig. 11 shows the control scheme, including current-loop control, speed-loop control, and network delays. The simulation of the step response is shown in Fig. 12.
F. Experimental Verification

The network-based control system has been built and implemented in our laboratory with customized PEBB platforms. The experiment structure and setup are shown in Figs. 13 and 14. The PEBB is controlled by a dSpace [22] platform model CP1104. A Virtual Test Bed (VTB) [23] schematic, which is called the VTB server and runs on a local PC, is capable of exchanging data with the CP1104 through Matlab workspace at runtime. The PI controller for the speed loop runs in another schematic called VTB client at remote PC. These two schematics communicate with each other through the TCP protocol. The communication with the PCs is achieved through an Ethernet network, allowing for the insertion of this device in the PC-based network of controllers.

Fig. 15 shows the motor’s speed step response when the speed reference is 30 and 40 rad/s in sequence. The steady state of the motor speed is shown in Fig. 16. To show the effects introduced by the network delay, a local control test without network communications involved is implemented, and experiment results are shown in Figs. 17 and 18.

From the two test results, we can see that the control bandwidth reduction introduced by the network implementation is not evident. From the steady-state results, it is clear that the main effect introduced by network delays in feedback and forward loop is a small but contained oscillation. As expected, while the delays inserted are in the range adopted for the design, the system is designed to be robust and performs a stable behavior.
VI. CONCLUSION

This paper has proposed a network-based control architecture for PEBB devices. A critical aspect in such a system is the management of a measurement affected by stochastic delay. The authors have outlined a design methodology for controllers operating with this type of measurements. In particular, an approach based on uncertainty analysis was proposed. The theoretical foundations of this approach have been discussed, together with the implementation and results of a physical laboratory prototype. Following this design procedure, one can design a network-based controller for other devices. This design procedure also provides an analytical way to design a robust controller for the systems with multi-uncertainties.

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