Tools to Address System Level Issues in Power Electronics: the Digital Network Analyzer Method and the Positive Feedforward Control Technique

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Abstract — The paper reviews two tools to address system level control issues in power electronic distribution systems: the positive feedforward control technique and the digital network analyzer method. Using the positive feedforward control technique, a DC-DC converter can at the same time control its output voltage and stabilize the input DC bus. The digital network analyzer method gives a converter the capability to measure small-signal transfer functions and impedances at its terminals. This information can be used for monitoring and control adaptation. Examples of applications of the two methods are described. 1

Index Terms — DC-DC converter control, multi-converter control, system identification, adaptive control

I. INTRODUCTION

In modern times there has been an increased penetration of power electronic converters into all types of power distribution systems due, on the one hand, to improvements in power electronic converter technology, and, on the other hand, to a demand for the improved performance and capabilities brought about by the adoption of these converters. Advances in various areas such as power semiconductor devices, magnetics, control, and converter topologies have made it possible to build high-performance converters at low cost. Power converters act as quasi-ideal power interfaces between a supply and a load. Therefore, they provide a way to effectively interconnect sources and loads having very different and incompatible electrical characteristics. Typical examples are in the area of renewable energy, where alternative energy sources such as photovoltaic panels (low-voltage DC power) and wind turbines (variable frequency AC power) must be interfaced to the grid (single-phase or three-phase fixed frequency AC power).

There has also been a general trend towards increased electrification in non-grid-connected applications. Electrical systems are replacing a number of other mechanical and hydraulic systems since new electric actuators and electric sensors provide a number of advantages such as speed of response, accuracy, flexibility, reliability, long life expectancy and decreased cost. A typical example is a modern car with electric actuators, such as throttle by wire, electronic power steering, and electronic braking. Other typical examples are electric and hybrid electric cars [1], more electric aircraft power systems [2], electric ships [3]-[4], and modern soldier weaponry [5].

Figure 1. Proposed MVDC power distribution system for US Navy all-electric ship (simplified)

In many applications these power-electronic-enabled electrical power distribution systems appear as a complex and extensively interconnected multi-converter system, with power converters feeding other power converters [6]. In this paper we will focus on DC power electronic distribution systems (PEDS). An example of these DC PEDS is the proposed medium voltage DC (MVDC) power distribution system for the US Navy’s all-electric ship shown in Figure 1. This system has a DC bus, shown in the center, powered by several power sources and power storage devices, such as turbine generators, fuel cells, batteries and flywheels, shown on the left hand side of the figure. The PEDS powers several loads, such as propulsion motors, actuators, sensors and power weapons, shown on the right hand side of the figure. Notice that all sources and loads are interfaced to the DC bus via a power electronic converter interface. Benefits of this system are (1) elimination of bulky 60Hz isolation transformers replaced by smaller high frequency transformers operating at the power electronic converter switching frequency, with

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associated reduction in size and weight; (2) elimination of circuit breakers, because properly designed power electronic converters can limit short circuit currents through their control [Dougal]; (3) elimination of the need for synchronization between generators required in AC power distribution systems; (4) improved survivability due to the increased flexibility provided by the power electronic converter controllers; and (5) improved efficiency due to reduction in the number of power conversion stages between sources and loads.

Together with these advantages come system-level challenges related to system stability and design of individual converter feedback loops that guarantee proper operation of the interconnected system. This paper discusses two tools to address these problems: the positive feedforward control technique [7]-[9] and the digital network analyzer method for switching converters [10]-[13]. The analysis and design of single power converters and their controls is well understood [14]. The analysis and design typically assume ideal supply voltage and resistive loads. Feedback controls are developed under these assumptions and typically perform well as long as these assumptions are satisfied. Each converter is viewed as a standalone system with limited interactions with other systems. These interactions are usually viewed as un-modeled disturbances and are examined only after the converter design is completed, possibly in a global computer simulation. This approach is viable as long as only one or at most a few power converters are present in a system.

However, in PEDS systems the situation is different. A number of system-level issues arise due to interactions among various power converters. A power converter that was performing satisfactorily when tested as a standalone unit may experience degradation in performance when connected to other power converters in a system. Since each converter has a closed-loop control, this is a multi-loop control problem, where loop interactions may change the control bandwidth substantially from the standalone case and may compromise control stability both at the converter and system level. Analyzing and designing a complex multi-converter system in such a way as to guarantee system stability and performance is a complex problem that is still not well understood. The difficulties stem from a lack of adequate analysis and design tools, limited understanding of the problem, difficulties in applying the existing stability criteria, and the need for stabilizing converter controllers, since frequently the interconnected system ends up being open-loop unstable due to the converter interactions. In particular a closed-loop power converter appears as a constant power load at its input and therefore presents potentially destabilizing negative incremental impedance at the input DC bus. Moreover, the system configuration varies over time due to reconfiguration, upgrades, introduction of additional sources or loads, so that an individual power converter sees different input and output equivalent impedances over time.

The two techniques discussed in this work address these problems.

The positive feedforward (PFF) control technique addresses the destabilizing effect of converters on the input bus. Using this technique, the converter is controlled in such a way that it has a stabilizing effect on the input bus in a certain frequency range.

The digital network analyzer method addresses the problem of variable system configuration. The converter itself becomes the excitation source and analysis tool used to measure transfer functions and impedances at its input and output ports. In particular, the DC input bus impedance can be measured, so that variations can be monitored and the converter control can take appropriate actions to maintain overall system stability.

II. POSITIVE FEEDFORWARD CONTROL

A general representation for a converter in a DC PEDS is shown in Figure 2. Impedance $Z_s$ is a lumped representation of the source as seen at the input terminal of the converter, and impedance $Z_L$ is a lumped representation of the load as seen at the output terminal of the converter. An input voltage feedforward controller $G_{CFF}$ and output voltage feedback controller $G_{CFB}$ are also shown in Figure 2. A standalone converter would have an ideal voltage source at the input ($Z_s = 0$) and a purely resistive load at the output ($Z_L = \infty$), assuming the load resistance is considered part of the converter box). Therefore, converter interactions are modeled by the effects of impedances $Z_s$ and $Z_L$ having nonzero and finite values respectively.

![Figure 2. A regulated converter with the lumped output and input impedances of source and load subsystems](image)

A. Advantages of PFF Control

In this work we examine the frequently negative effect on system stability of the introduction of a non-zero source impedance $Z_s$, and consider a control structure that can improve system stability. The proposed approach is to add to the conventional output voltage negative feedback (NFB) control an input voltage PFF control, which improves stability margin by controlling the converter as an active filter in a certain frequency range. This active approach should be compared with conventional passive approaches such as power filter damping or the addition of decoupling capacitors at the converter input. However, unlike those passive approaches, the proposed active approach using PFF control is particularly attractive in that...
the stability improvement is achieved by control action only, with no hardware modification of the physical system. The elimination of large decoupling capacitors is particularly important in DC PEDS systems, because these capacitors significantly increase transient fault current in case of a line-to-ground fault [15]. Furthermore, the PFF control stabilizing effect may be tuned online using an adaptive control approach to compensate for variations of the source impedance. One possibility is to perform an online measurement of the source impedance utilizing the digital network analyzer technique discussed later in the paper.

By utilizing both the positive feedforward and feedback control actions, the controller can regulate both the input and output characteristics of a converter. Obviously, there are trade-offs between what input and output characteristics can be achieved. By adjusting the control actions, it is possible, within limits, to tailor the desired input and output terminal characteristics of the converter. In other words, the PFF control regulates input port characteristics of the converter at high frequencies so that the converter acts as an active filter, while the NFB control tightly regulates the output voltage at low frequencies so that the converter behaves as a conventional feedback control system.

B. Positive vs Negative Feedforward Control

It is crucial to appreciate the qualitative difference between the proposed positive feedforward control and the conventional feedback control, which we will call negative feedforward control.

On the one hand, the objective of conventional negative feedforward control is to minimize the effect of input voltage variation on the output voltage. The input voltage is measured and used for control, so that the controller can react faster to input voltage variations, since an input voltage perturbation does not need to propagate to the output in order to elicit a controller response. The end result is that the effect of input voltage perturbations on the output voltage is more readily suppressed by the controller. This improves output voltage regulation, but it has a destabilizing effect on the input port. As explained above, the converter’s closed-loop input impedance has a negative real part at low frequency; the introduction of negative feedforward control extends the bandwidth of the control and therefore the negative real-part of the input impedance extends to higher frequencies.

On the other hand, the objective of PFF control is to stabilize the input voltage over a desired frequency range. As will be discussed later, the input voltage stabilization occurs in the frequency range where the input feedforward control gain is larger than the output feedback control gain.

C. Small-signal Converter Modeling

The small-signal model of the open-loop converter is shown in Figure 3. The converter can be considered as a three-input two-output system described by the matrix equation

\[
\begin{bmatrix}
    i_{in} \\
    \hat{v}
\end{bmatrix} =
\begin{bmatrix}
    \frac{1}{Z_{in,OL}} & G_{id,OL} & G_{ii,OL} \\
    G_{ig,OL} & G_{vd,OL} - Z_{out,OL} & -Z_{load}
\end{bmatrix}
\begin{bmatrix}
    \hat{v}_g \\
    d
\end{bmatrix}
\] (1)

The overall converter system of Figure 2 including source and load subsystems and feedforward and feedback control can be represented by the block diagram of Figure 4. Notice the feedback loops introduced by the source and load impedances. The feedback loop gain is

\[T_{FB} = G_{CFB}G_{vd,OL}\]

and the feedforward gain is given by

\[T_{FF} = G_{CFP}G_{id,OL}\]

Impedance \(Z_{N,vd,OL}\) is defined as the converter input impedance for the case of ideal feedback control, i.e., for a feedback controller that perfectly regulates the output voltage.

\[
\frac{1}{Z_{N,vd,OL}} = \frac{1}{Z_{in,OL}} - \frac{G_{id,OL}G_{vg,OL}}{G_{vd,OL}}
\] (4)

Impedance \(Z_{in, FFfB}\) is the closed-loop converter input impedance including the effects of feedforward (FF) and feedback (FB).

\[
Z_{in, FFfB} = \frac{1}{Z_{in, OL}} + \frac{1}{1 + T_{FB}} + \frac{1}{Z_{N,vd,OL}1 + T_{FB}} + \frac{T_{FF}}{1 + T_{FB}}
\] (5)

More details on the modeling approach can be found in [9].

![Figure 3. A block diagram for the small-signal model of the converter](image)

![Figure 4. A block diagram for the entire converter system including source and load subsystems and feedforward and feedback control](image)
The PFF controller can be designed using the well-known Middlebrook stability criterion [16] and its extensions. The effect of the non-zero source impedance $Z_S$ on converter stability can be studied as a function describing the loading effect of the converter on the non-ideal voltage source represented by the Thevenin equivalent $V_{gs} - Z_S$ introducing the so-called minor loop gain $T_{MLG, ZS}$ given by

$$ T_{MLG, ZS} = \frac{Z_S}{Z_{in, FF}} \frac{1}{1+T_{FB}} \frac{Z_S}{Z_N \cdot \nu d \cdot OL} \frac{T_{FB}}{1+T_{FB}} \frac{Z_S T_{FF}}{(1+T_{FB})} $$

(6)

This can be clearly seen by looking at the upper feedback loop in the block diagram of Figure 4. System stability can be established by studying the stability of a closed loop system having loop gain $T_{MLG, ZS}$. For PFF control design it is more appropriate to apply directly the Nyquist criterion to the impedance ratio (necessary and sufficient stability condition), rather than imposing a small gain constraint (sufficient stability condition), as done by the original Middlebrook criterion. The small-gain constraint ensures no interaction between source system and converter, but we actually desire a stabilizing interaction caused by the positive feedforward control. The feedforward controller $G_{CFF}$ and the feedback controller $G_{CFB}$ are designed in such a way that feedback control dominates at low frequency and feedforward control dominates at high frequency. The minor loop gain at low frequencies (for $|T_{FB}| \gg 1$, $|T_{FF}| \ll 1$) can be approximated as

$$ T_{MLG, ZS} = \frac{Z_S}{Z_{in, \nu d \cdot OL}} $$

(7)

which is identical to the feedback control case at low frequencies. Similarly at high frequencies (for $|T_{FB}| \ll 1$, $|T_{FF}| \gg 1$) the minor loop gain can be approximated as

$$ T_{MLG, ZS} = \frac{Z_S}{Z_{in, \nu d \cdot OL}} + Z_S T_{FF} = Z_S T_{FF} $$

(8)

In order to improve the stability of whole system, the third term in (6) should be properly designed so that it has higher gain and has a positive real part at high frequencies compared with the feedback control term.

The approach has been validated in simulation and experimentally. In the experiment a Buck converter with an undamped input filter is considered. Figure 5 shows source impedance $Z_S = Z_{OUT, ZS}$ (red trace), the converter input impedance with feedback only $Z_{in, FB}$, and the converter input impedance with feedforward control $Z_{in, FF}$. Interaction occurs in the frequency range where $Z_S$ is larger than $Z_{in, FB}$ (minor loop gain magnitude greater than 1, see (6)). The frequency range of interaction is actually larger for the PFF case, but the interaction brings about a phase margin improvement, as seen in the phase plot.

In the experiment the Buck converter with input filter is operated under feedback control (Figure 6) and under positive feedforward control (Figure 7). A constant power load is applied to the input DC bus to represent the effect of other closed-loop controlled converters connected to the same bus. A step load is applied to the converter. The blue trace (second from top) shows the converter input voltage waveform. In the feedback control case, there is significant ringing, whereas in the positive feedforward case the ringing is well damped by the control. This demonstrates...
the stabilizing action of the control. It is also important to note the improvement on the converter’s output voltage regulation as an effect of the input voltage stabilization.

III. DIGITAL NETWORK ANALYZER TECHNIQUE USING SWITCHING CONVERTERS

The digital network analyzer technique is the second tool to address system level issues in PEDS. This technique uses a switching converter as a perturbation source, and its controller as a signal analyzer to measure small-signal transfer functions and impedances of interest. Referring to Figure 8, a pseudo-random binary sequence (PRBS) test signal is added to the duty cycle signal from the feedback controller. Applying the cross-correlation technique to the appropriate measured quantities allows online monitoring of quantities internal to the converter, such as control-to-output transfer function $G_{vd}(s)$, loop gain $T_{loop}(s)$, and of quantities looking outward from the converter, such as source system impedance $Z_{source}(s)$ and load system impedance $Z_{load}(s)$.

![Figure 8. Conceptual block diagram showing injection of a test signal into the control channel](image)

Figure 8 shows a number of distribution system changes that can affect the converter under test, such as multi-converter interactions, loss of a converter due to battle damage or failure, load changes and source impedance changes. The proposed technique provides a method for online monitoring of the effects of these changes on the converter dynamics. Online measurement of these quantities can be used for system monitoring, fault detection and localization, stability and performance monitoring, stability improvement using adaptive control, and for distributed control.

### A. Theory

A switching converter operating at steady state can be considered a linear time-invariant system to small-signal disturbances [14]. The sampled system can be described by

$$y(n) = \sum_{k=-\infty}^{\infty} h(k)u(n-k) + v(n) \quad (9)$$

where $y(n)$ is the sampled output signal, $u(k)$ is the sampled input signal, $h(k)$ is the discrete-time system impulse response, and $v(n)$ represents unwanted disturbances such as switching and quantization noise. The cross-correlation of the input control signal $u(k)$ and the output signal $y(k)$ is defined in (10) as:

$$R_{y\!y}(m) = \sum_{n=-\infty}^{\infty} u(n)y(n+m)$$

$$= \sum_{n=-\infty}^{\infty} h(n)R_{uu}(m-n) + R_{u\!v}(m) \quad (10)$$

where $R_{uu}(m)$ is the auto-correlation of the input signal, $R_{y\!u}(m)$ is the input-to-output cross-correlation, and $R_{u\!v}(m)$ is the input-to-disturbance cross-correlation [17]. Consider white noise as a choice of input test signal $u(k)$. White noise input exhibits the following properties:

$$R_{uu}(m) = \delta(m)$$
$$R_{u\!v}(m) = 0 \quad (11)$$

where $\delta(m)$ is the discrete unit impulse sequence. These properties allow simplification of equation (2) such that the input to output cross-correlation becomes the discrete-time system impulse response [17]

$$R_{y\!u}(m) = h(m) \quad (12)$$

The discrete-time system impulse response can be transformed into the system frequency response using a Discrete Fourier Transform (DFT),

$$G_{y\!u}(s) = DFT\{h(m)\} \quad (13)$$

The cross-correlation method as described so far allows the estimation of the transfer function from the control variable, where the perturbation is added, to a measured variable. In switching converters the control signal is usually duty cycle, so the method can be used to find the control-to-output transfer function $G_{vd}(s)$. To measure a transfer function between two measured variables different from the control, two control-to-variable transfer functions are measured and combined together. For example, the measurement of impedance requires a voltage or current perturbation at the interface and measurements of both voltage and current. Since impedance is defined as the ratio of voltage variations to current variations, this ratio must be constructed from two measurable transfer functions: control-to-voltage, $G_{vd}(s)$, and control-to-current, $G_{id}(s)$. This construction is shown in (14) and (15).
Z(s) \equiv \frac{\hat{v}(s)}{i(s)} = \frac{G_{vd}(s)}{G_{id}(s)} \quad (14)

G_{vd}(s) \equiv \frac{\hat{v}(s)}{d(s)} ; G_{id}(s) \equiv \frac{i(s)}{d(s)} \quad (15)

The source impedance measurement is depicted in Figure 10.

Figure 10. Source impedance measurement

B. Improvements and Extensions to the Cross-correlation Method

The properties presented in (11) that allow the simplifications leading to (12) assume a purely random white noise, which is impossible to create in practice using a finite-length sequence.

The authors have proposed several techniques for improving transfer function identification accuracy, particularly at high frequencies near the desired closed-loop bandwidth [10], [12]. The first method delays the output voltage sampling by half of the sequence clock period to offset the phase shift caused by the zero-order hold interface. Second, a window function is applied to the input-to-output cross-correlation data to suppress the spurious high-frequency content caused by the non-ideal auto-correlation of the test sequence. Third, signals other than white noise can be used to improve accuracy. For example, in systems exhibiting lowpass characteristics the signal-to-noise ratio at high frequency may be compromised. It is then possible to use a perturbation signal with enhanced high frequency content, such as blue noise, to improve accuracy. Finally, a correction is made to the control-to-output transfer function by dividing by the spectrum of the injected perturbation sequence to reduce the phase uncertainty and to correct for colored noise if used instead of white noise. The authors have also extended the method to measure loop gain without opening the feedback loop.

C. Experimental Results for Transfer Function and Impedance Estimation

A Buck converter with an L-C input filter operating at 100kHz has been built to experimentally validate the approach as shown in Figure 11. Examples of experimental measurements compared to network analyzer measurements are shown in Figure 12 for the control-to-output transfer function and in Figure 13 for the converter loop gain. The results show good matching up to approximately 25kHz, which is one half of the Nyquist frequency (50kHz).
Impedance measurements are also performed to measure the source impedance given by the L-C input filter and the load impedance for the three cases shown in Figure 11. Figure 14 shows the load impedance measurement for the L-R-C load case. Results for the other cases can be found in [12].

D. Adaptive Control – an Application of Proposed System Identification Technique

An example of the application of this technique to adaptive control is now briefly described and simulation results are presented. The control platform can use the converter to perturb the system, identify the non-parametric frequency response of the plant, fit the data to a parametric model, and synthesize a control which meets user specifications. Details can be found in [11].

A switching converter with the adaptive controller structure is shown in Figure 15 and the adaptive control method is shown in Figure 16.

The converter is perturbed with a PRBS sequence and the system responses are recorded. Cross-correlation analysis gives a non-parametric description of the control-to-output transfer function $G_{vd}(j\omega)$. Least-squares fitting is used to obtain an approximation of the transfer function having a desired number of poles and zeros. The adaptive controller parameters are synthesized using the Internal Model Control (IMC) approach [18] and the digital controller is updated.

The approach is validated by simulation in Matlab/Simulink. The basic schematic of the converter system is shown in Figure 17. Each test case involves a variation of one of the converter parameters in the red dashed circles: output bus capacitance, output capacitor ESR, downstream constant power load, and undamped LC input filter. For space reasons, only results for the case of variation of output bus capacitance are shown.

The output-voltage-reference step before control adaptation is shown in Figure 18, where a significantly less-damped step response is observed with respect to the nominal case, also shown. The identification and fitting of the off-nominal control-to-output frequency response is shown in Figure 19 and features a lower output filter corner frequency and increased Q when compared with the nominal case (not shown). After a new control is synthesized and re-engaged, the improved step response of the converter is shown in Figure 20. This result clearly shows the improvement obtained with the adaptive control.
useful tools to address these challenges are discussed. The positive feedforward technique allows a converter to acts as a stabilizer at its input while still performing its basic function of power delivery at its output. The digital network analyzer technique provides online monitoring of system transfer functions and impedances and opens interesting new possibilities for online system monitoring and control adaptation.

References