Adjustable Shunt Regulator Based Control Systems

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***Abstract*—Adjustable shunt regulators known as TL431 are extensively used to build the control systems in switched-mode converter applications. The resulting control system is typically a two-loop system, where one loop defines the low frequency behavior, and the other loop the higher frequency behavior, respectively. The shunt regulator is regarded to possess characteristics similar to an operational amplifier, even if it is basically a transconductance amplifier having current as an output signal instead of voltage as well as positive feedback instead of negative feedback. The small-signal response of a shunt regulator shows that it may be modeled as a voltage-controlled current source with a small transconductance gain and an equivalent capacitor as output impedance, which may be extracted from the open-loop frequency response by inspection. The variance in the parameters may be high depending on the manufacture, and operating point, i.e., cathode current, which is normally chosen to be close to 1 mA due to the specifications. The analysis shows, however, that the cathode current should be at least 5 mA for stable equivalent circuit parameters. If low cathode current is used, the control system may not be better than a Zener diode replacing the shunt regulator.**

***Index Terms*—Control, shunt regulator, switched-mode converter.**

I. Introduction

ADJUSTABLE shunt regulators such as e.g. [1]–[4], commonly known as TL431 and developed in the late 1970s [1], are extensively used as a basis for switched-mode-converter control, especially in low-cost high-volume applications [5]–[7]. This is due to the simplicity of building the control system; the output of the shunt regulator may be used directly to drive an optocoupler isolating the control loop and a very low number of additional components is needed for a controller implementation [8]. A typical structure of such a controller is shown in Fig. 1.

Typically the shunt regulator is connected to the system in such a way that both the cathode (i.e., via optocoupler diode) and the reference input are connected to the output voltage forming a two-loop control system [5]–[11] known [10] as fast loop and slow loop (Fig. 1) due to their dominating frequency ranges. The slow loop is considered to introduce negative feedback similarly to operational amplifiers [5]–[7]. The reference input is, however, a noninverting input and therefore, both of the loops are positive feedback loops in respect to the output current of the control system. The shunt regulator

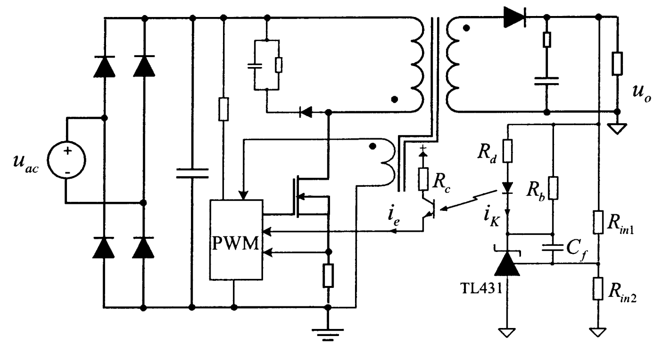

Fig. 1. TL431 based control system in a battery charger application.

is a transconductance amplifier [9] that may be modeled as a voltage-controlled current source with a transconductance gain and output impedance. The open-loop frequency response given typically in respect to the cathode-anode voltage [1]–[5] shows that a constant transcondcutance gain and an output capacitor may be sufficient for representing the internal dynamics of a shunt regulator. The low-frequency part of the frequency response may represent the transconductance gain multiplied by the cathode termination resistor, and the cut-off frequency the inverse of the output capacitance multiplied by the cathode termination resistance, respectively. The frequency response and its corresponding test set-up shown in [5] may not be utilized for the parameter extraction, because the cathode termination resistor is not specified. When comparing the frequency responses shown, e.g., in [1] and [3], it may be obvious that the equivalent circuit parameters may have large manufacturer-based variations. The described dynamical deficiencies are not typically considered in the loop-gain analysis as, e.g., in [5]–[7] even if they may have crucial effects on the control system behavior.

We will present in this paper a more detailed analysis of a shunt regulator based control system. It will be pointed out that the dynamical deficiencies due to rather large manufacturer-based variation, and operating point dependence should be carefully taken into account for robust controller design. The associated two-loop system is not well known among the practising engineers due to the assumption that it operates like an operational amplifier.

The notation conventions in this paper are as follows. The capital letters denote the *DC* values or *Laplace* variables, the hatted small letters *ac* or *perturbed* values, and the small letters *total* values of associated quantities, i.e., the sum of *DC*, and *ac* values of the associated variables.

II. Shunt Regulator as Transconductance Amplifier

A high-level equivalent circuit of a shunt regulator may be presented as shown in Fig. 2 where the output stage is imple-

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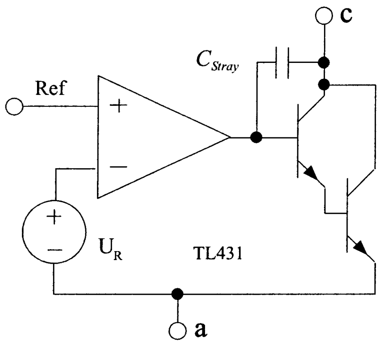

Fig. 2. High-level equivalent circuit.

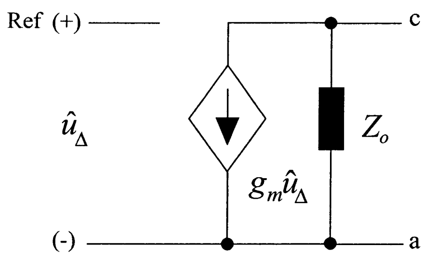

Fig. 3. Small-signal equivalent circuit.

mented as a Darlington stage [1]. The capacitor between the base of the Darlington stage and the cathode is reflected as output impedance (Z_o) shown in Fig. 3. The equivalent circuit parameters may be extracted from the frequency response data usually presented in the associated data sheets in respect to the cathode-anode voltage (i.e., u_{KA}) [1]–[4]. The frequency response displays first-order behavior, where the low-frequency gain corresponds to the product of the cathode termination resistor and the transconductance gain g_m, and the cut-off frequency to the inverse of the product of the equivalent output capacitance (i.e., Z_o, Fig. 3) and the cathode termination resistance. A 232 Ω resistor is commonly used as the termination resistor [1], [2] but may vary among different manufacturers [3]. The low frequency gain is typically from 50 to 60 dB corresponding to g_m from 1.36 Ω^{-1} to 4.3 Ω^{-1}, respectively. The typical cut-off frequency [1], [2] is about 10 kHz corresponding to an output equivalent capacitor of 70 nF. Some of the shunt regulators [3] seem to have a higher gain output stage. This results in higher g_m and output capacitor, 22.5 Ω^{-1} and 3.2 μF, respectively.

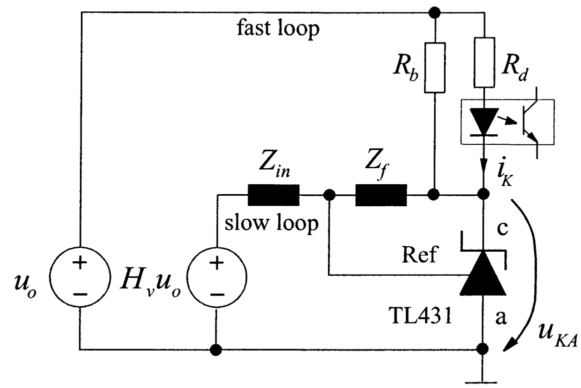

Fig. 4. Typical control system based on TL431.

III. Control System

A typical control system built around TL431 is shown in Figs. 1 and 4, where H_v is the output voltage sensing gain, and Z_{in} its Thevenin impedance. From the loop gain point of view, the essential transfer function is the transfer function from the output voltage u_o to the current i_K flowing trough the diode portion of the optocoupler. This transfer function is actually a sum of the slow and fast loop transfer functions, which may be computed from Fig. 4 utilizing the small-signal equivalent circuit of TL431 shown in Fig. 3. The bias resistor R_b (Fig. 4) is typically much larger than R_d (i.e., 1 kΩ vs. 10 Ω) having therefore, no effect on the system dynamics.

See (1)–(3) at the bottom of the page. The resulting slow (i_K/u_{o-s}) and fast (i_K/u_{o-f}) loop transfer functions are defined in (1) and (2), respectively. The notations used in (1) and (2) (Fig. 1) are specified in (3).

If considering a control system of the proportional-integral (PI) type (i.e., $Z_f = R_f + 1/sC_f$), the general transfer functions in (1) and (2) may be developed as shown in (4) and (5). The same transfer functions according to [5]–[7] are (7) and (8).

$$\frac{\hat{i}_K}{\hat{u}_{o-s}} = \frac{H_v g_m \left(1 + s\left(R_f - \frac{1}{g_m}\right) C_f\right)}{A} \tag{4}$$

$$\frac{\hat{i}_K}{\hat{u}_{o-f}} = \frac{s^2(R_{in}+R_f)C_f C_o + s(C_f + C_o)}{B} + \frac{sR_{in} g_m C_f \left(1 + s(R_{in}+R_f)C_f\right)}{A \cdot B} \tag{5}$$

$$\frac{\hat{i}_K}{\hat{u}_{o-s}} = \frac{H_v Z_o (Z_f g_m - 1)}{(Z_{in}+Z_f)(R_d+Z_o) + R_d Z_o (1 + Z_{in} g_m)} \tag{1}$$

$$\frac{\hat{i}_K}{\hat{u}_{o-f}} = \frac{Z_{in}+Z_f+Z_o}{(Z_{in}+Z_f)(R_d+Z_o)+R_d Z_o} + \frac{Z_{in} Z_o^2 (Z_{in}+Z_f) g_m}{\left((Z_{in}+Z_f)(R_d+Z_o)+R_d Z_o\right)\left((Z_{in}+Z_f)(R_d+Z_o)+R_d Z_o(1+Z_{in} g_m)\right)} \tag{2}$$

$$Z_{in} = \frac{R_{in1} R_{in2}}{R_{in1}+R_{in2}} \qquad H_v = \frac{R_{in2}}{R_{in1}+R_{in2}} \tag{3}$$

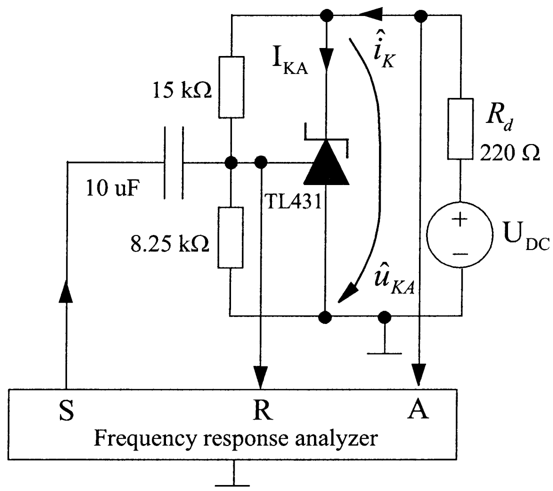

Fig. 5. Open-loop frequency-response test setup.

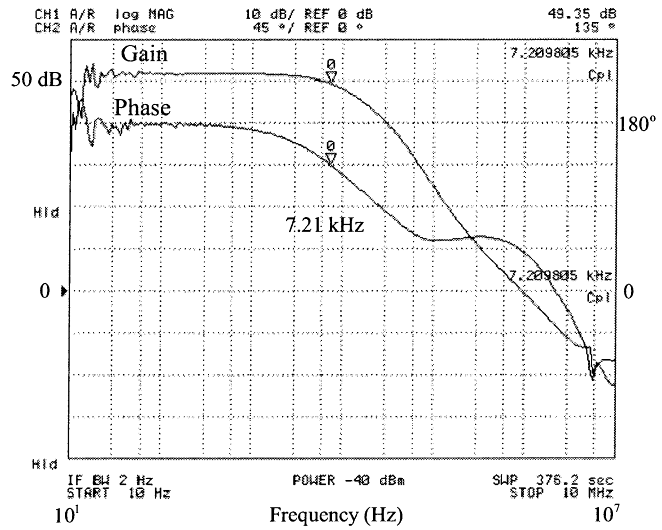

Fig. 6. Open-loop frequency response for TL1431 [4] at $I_{KA} = 10$ mA. The low-frequency gain (upper curve) is approximately 52 dB, and the cutoff frequency 7.2 kHz. The phase is the lower curve.

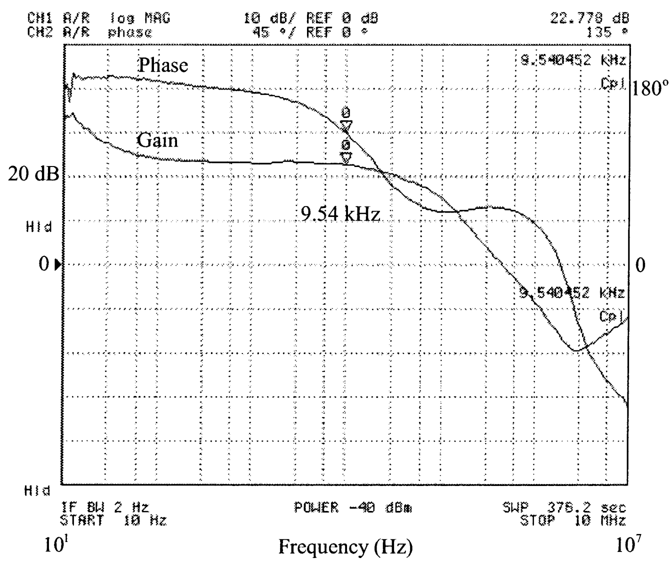

Fig. 7. Open-loop frequency response for TL1431 [4] at $I_{KA} = 1$ mA. The low-frequency gain (lower curve) is approximately 24 dB, and the cut-off frequency 9.5 kHz. The phase is the upper curve.

where A and B are as follows

$$\begin{aligned} A &= s^2\,(R_{in}+R_f)R_dC_fC_o+s \\ &\quad \cdot((R_{in}+R_f+R_d(1+R_{in}g_m))\,C_f+R_dC_o)+1 \\ B &= s^2(R_{in}+R_f)R_dC_fC_o \\ &\quad +s\,((R_{in}+R_f+R_d)C_f+R_dC_o)+1 \end{aligned} \tag{6}$$

$$\frac{\hat{i}_K}{\hat{u}_{o-s}} = -\frac{H_v(1+sR_fC_f)}{R_d s R_{in} C_f} \tag{7}$$

$$\frac{\hat{i}_K}{\hat{u}_{o-f}} = \frac{1}{R_d}. \tag{8}$$

The maximum gain of the slow loop is $H_v g_m$ up to the low-frequency pole located approximately at $1/R_{in}R_dg_mC_f$ after which the gain decreases with slope -20 dB/dec up to the zero $1/R_fC_f$. If comparing the actual slow-loop behavior to (7), the main differences are the limited low-frequency gain, and phase behavior. The fast loop behaves as a derivative loop up to the same low-frequency pole as the slow loop after which its maximum gain is close to $1/R_d$. This is because the zeros and poles, except the slow-loop pole, are typically located close to each other, and are, therefore, effectively cancelled. If the transconductance gain g_m is small, the control system response corresponds to $1/R_d$ or is equal to the use of a Zener diode instead of the shunt regulator.

IV. Experimental Shunt Regulator Analysis

The open-loop frequency responses of certain shunt regulators were measured using the test setup shown in Fig. 5. The open-loop frequency responses are normally given using the cathode current $I_{KA} = 10\,\mathrm{mA}$ [1]–[4]. The minimum operating current is recommended to be at least 1 mA [1]–[4]. Therefore, the bias resistor R_b (Fig. 4) is chosen typically in such a way that the 1 mA requirement is met, and therefore, the overall cathode current may be only slightly more than 1 mA. Fig. 6 shows the measured frequency response for TL1431 [4] at the cathode current of 10 mA. The first-order nature is obvious, and the resulting parameters are $g_m = 1.81\ \Omega^{-1}$ and $C_o = 100$ nF. The open-loop frequency response at the cathode current of 1 mA is shown in Fig. 7 showing a dramatic reduction of transconductance gain from 1.81 Ω^{-1} to 0.07 Ω^{-1}. The equivalent capacitor value is only slightly reduced from 100 nF to 75 nF. This test shows that the equivalent circuit parameters will stabilize when the cathode current reaches about 5 mA.

V. Control System Frequency Response

The control system in Fig. 1 having $R_{in} = 9.17\ \mathrm{k}\Omega$, $C_f = 100$ nF, $H_v = 0.49$, and $R_d = 30\ \Omega$ was analyzed using g_m and C_o as 0.07 Ω^{-1}, 44 nF; 0.234 Ω^{-1}, 41 nF; 0.33 Ω^{-1}, 35 nF, and 0.45 Ω^{-1}, 30 nF corresponding to $I_{KA} = 1$ mA, 2 mA, 3 mA, and 10 mA, respectively, for a certain shunt regulator as well as 22.5 Ω^{-1}, 3.2 μF for the shunt regulator specified in [3]. The results of the analysis are shown in Fig. 8, and compared to an ideal model, where g_m is infinite and C_o is zero. The model

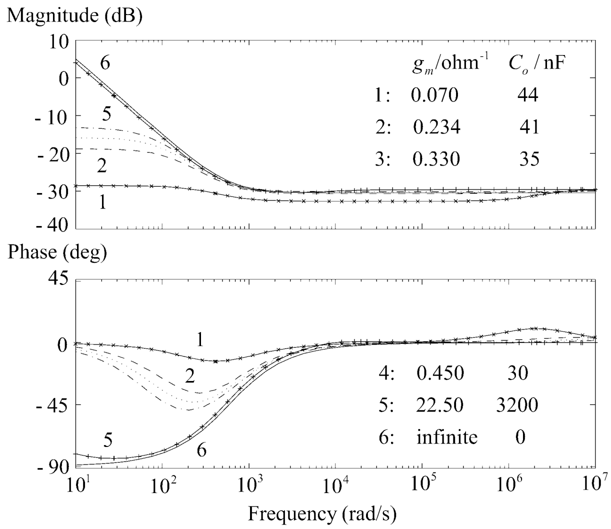

Fig. 8. Frequency responses of an integrating type control system (Fig. 1) with varying equivalent circuit parameters.

used in [5]–[7] would give a response, where the magnitude is the ideal amplitude but the phase starts from $+90°$ instead of $-90°$ shown in Fig. 8. It may be obvious that in the worst case (Fig. 8, response 1), the control system is not much better than a Zener diode connected in series with an optocoupler diode. In the case of PI control, the variability in amplitude and phase would be higher, increasing the uncertainty of the control system integrity.

VI. Conclusions

The frequently used shunt regulator known as TL431 was analyzed and modeled. It was noticed that the dynamics of the shunt regulator differ drastically from the assumptions made from its behavior. It was shown that a shunt regulator might be effectively modeled as a voltage-controlled current source with a constant transconductance gain and an equivalent capacitor as output impedance. These equivalent circuit parameters may be extracted from the open-loop frequency response but are highly dependent on the manufacturer and the operating-point cathode current. In the worst case, the resulting control system would not be much better than using a Zener diode instead of the shunt regulator. The observed dependence of the gain on the level of the cathode current may result in a high variability of the system gain at the frequencies near the typically used control system bandwidth.

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