Three-loop feedback control of fault-tolerant power supplies in IBM Enterprise System/9000 processors

by K. R. Covi

In an Enterprise System/9000™ (ES/9000™) processor, a fault-tolerant power system composed of multiple power supplies connected in parallel provides thousands of amperes of current to low-voltage (1–2 V) logic circuit boards, monitors the voltage at each board, and immediately responds to compensate for failure of a supply. If a supply fails, the very fast closed-loop response redistributes the current uniformly among the remaining supplies and allows the normal functioning of the processor logic to continue uninterrupted. This rapid response is not obtained from a conventional two-loop (current-mode) feedback power supply because the loop bandwidth is restricted by a resonance that develops in the power distribution. A third feedback loop that is added to each supply controls this power distribution resonance and makes possible the wide loop bandwidth necessary to achieve the required power system control. Analysis is presented of a three-loop control system, and a simulation of its application to a typical ES/9000 power system is described.

Introduction

Power supplies for today's mainframe computer systems are required to continuously deliver thousands of amperes (A) of current to low-voltage logic circuit loads without affecting computer system availability. To maintain operation of the power system, a modular approach is used in which multiple high-current power supplies are connected in parallel to form a single, high-current power bus. The supplied power is uniformly distributed over $N + 1$ supplies, where N supplies are sufficient to provide the full load current. A fault-tolerant power system is achieved by including a redundant power supply and by immediately redistributing the load current if one supply fails.

A well-designed redundant power system maintains good regulation of the power bus voltage. When a power supply fails, a transient-voltage perturbation appears on the power bus because of a sudden loss of output current from the faulty supply until the N remaining supplies adjust their output current. This disturbance is minimized by sharing the load current equally among each of the $N + 1$ power supplies.

Sharing load current equally among supplies establishes the initial conditions for minimizing the response times to failure of a supply. The feedback circuits that control the power bus voltage and sense when a voltage disturbance has occurred rapidly provide corrective action to bring the bus voltage back to normal. The limiting factor in obtaining a true fault-tolerant power system is the ability of the control circuits to minimize the amplitude of a voltage transient when a supply fails.

Power control system

The Enterprise System/9000™ (ES/9000™) power system is composed of multiple power supplies which are full-bridge, pulse-width-modulated, switching voltage regulators connected in parallel. A schematic diagram of the power lines and control circuits of a typical supply is shown in **Figure 1**. In the full-bridge circuit, diagonal pairs of switching transistors are alternately switched on and off at a high frequency (50 kHz). The ac input voltage across the primary of the power transformer is consequently switched between $\pm V_{\text{in}}$. This voltage is stepped down by the transformer and is then rectified and smoothed by a two-stage inductor/capacitor averaging filter to provide a dc output voltage [1]. The output voltage is controlled by varying the duty cycle of the switching transistors and is increased by increasing the switch duty cycle.

In recent years, current-mode control of switching power supplies has gained wide acceptance [2]. Current-mode control is a two-loop control method in which one internal high-speed loop provides control of the switch current and an external slower loop regulates the output voltage. With current-mode control, the duty cycle of the switching transistors is not directly controlled. Each pair of switches is cycled at fixed intervals by a clock, with one pair remaining on until a threshold current passing through the switches generates a turn-off signal. The threshold current is determined by the output of an error amplifier, which compares the power bus voltage to a fixed reference voltage. Since the current through the switches is proportional to the current through an inductor, L_1 (Figure 1), the inductor current becomes a function of the error signal, rather than the voltage across the inductor. The current-feedback loop transforms the power supply from a voltage source to a controlled current source. Since the error signal adjusts for differences between the bus and reference voltages, the voltage-feedback loop effectively controls the output current and tightly regulates the power bus [3].

Difficulties with two-loop control were encountered when it was adopted for use in the ES/9000 power system. A typical system consisting of two power-supply modules connected in parallel is shown in **Figure 2**. In addition to a two-stage averaging filter contained in each power supply, the parasitic inductance (L_3) of the power bus forms an additional filter with the bus-decoupling capacitor (C_3). The interaction of these three LC filters results in the formation of three resonant frequencies defined as follows:

$$\omega_1 = \text{low-frequency resonance } (f_1 = 1\text{ kHz}) = \frac{1}{\sqrt{(L_1 + L_2 + L_3)C_3}}, \tag{1}$$

$$\omega_2 = \text{mid-frequency resonance } (f_2 = 3\text{ kHz}) = \frac{1}{\sqrt{L_3 C_2}}, \tag{2}$$

$$\omega_3 = \text{high-frequency resonance } (f_3 = 27\text{ kHz}) = \frac{1}{\sqrt{L_2 C_1}}. \tag{3}$$

Since the high-current logic loads typically operate at 1–2 V, regulation of dc voltage at the circuit level to within 1% of the 1–2-V operating voltage used for high-current logic loads requires that the bus voltage on the logic board be maintained to within 10–20 mV. Because of the high currents involved, the power bus voltage must be sensed on the logic board, rather than at the output of the power supplies, to avoid the large ohmic voltage drops that are caused by the resistance of the bus distribution. Consequently, the three power-stage resonances originate within the feedback loops of the control circuits.

In the system shown in Figure 2, conventional two-loop control consists of feedback of the L_1 inductor current through current loop controller F_1, and of the bus voltage on the logic board through remote-voltage loop controller F_R. The low-frequency resonance at ω_1 is controlled by feedback of the L_1 inductor current for L_1 much greater than L_2 and L_3, a condition that is consistent with normal design practice [4]. The high-frequency resonance, formed by the interaction of L_2 and C_1 in the output filter of each power supply, is intentionally increased to avoid control problems. The mid-frequency resonance, however, degrades the performance of the two-loop feedback control system, since the bandwidth of the voltage-feedback loop is required to be much lower than ω_2 to avoid instabilities in the control system. The resultant low-bandwidth control loop is unable to respond rapidly enough to compensate

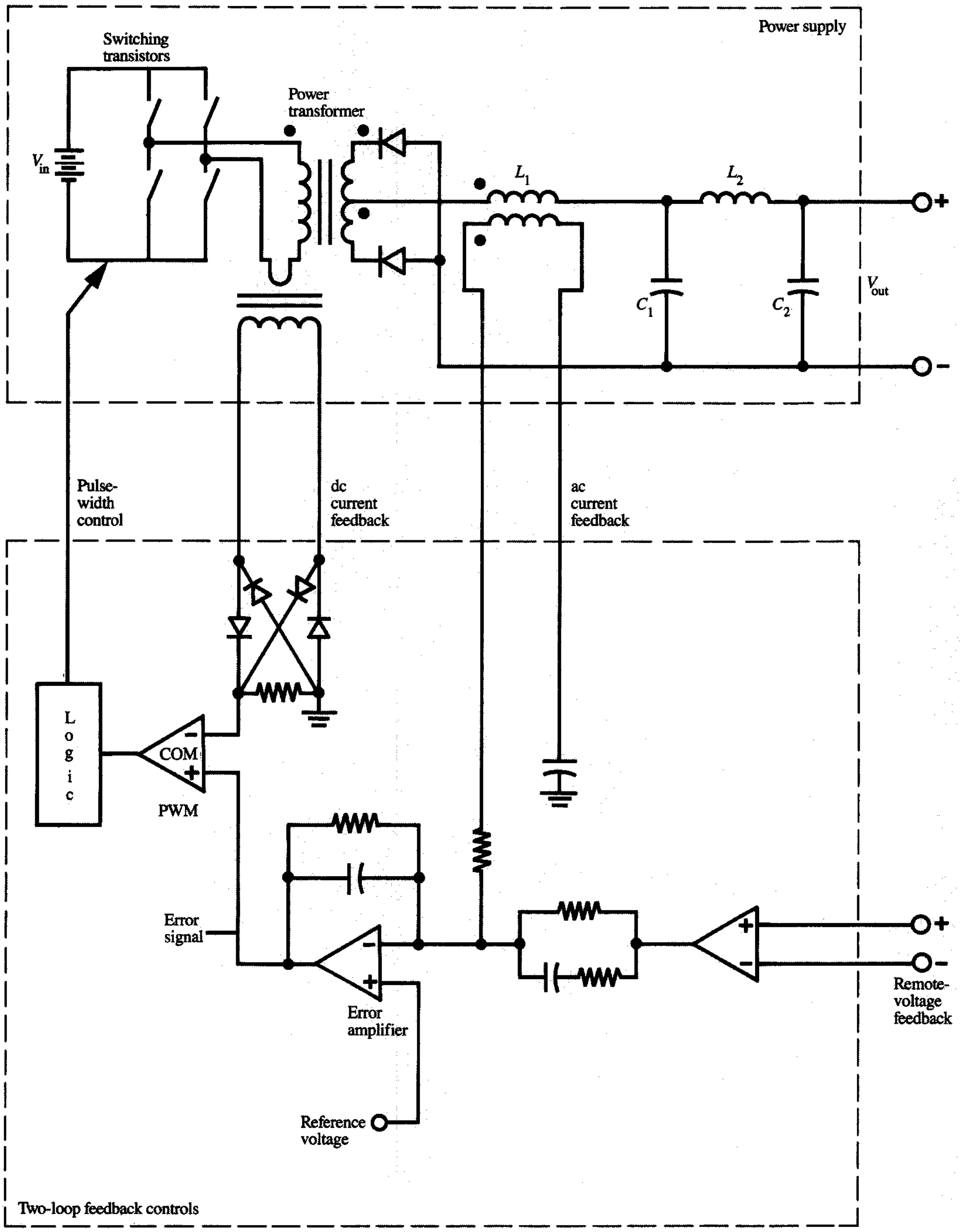


Figure 1

Power supply module with two-loop feedback controls.

for a sudden failure of a supply. The unsatisfactory closed-loop performance obtained with a conventional two-loop control system led to the development of a three-loop control system, removing the mid-frequency resonance.

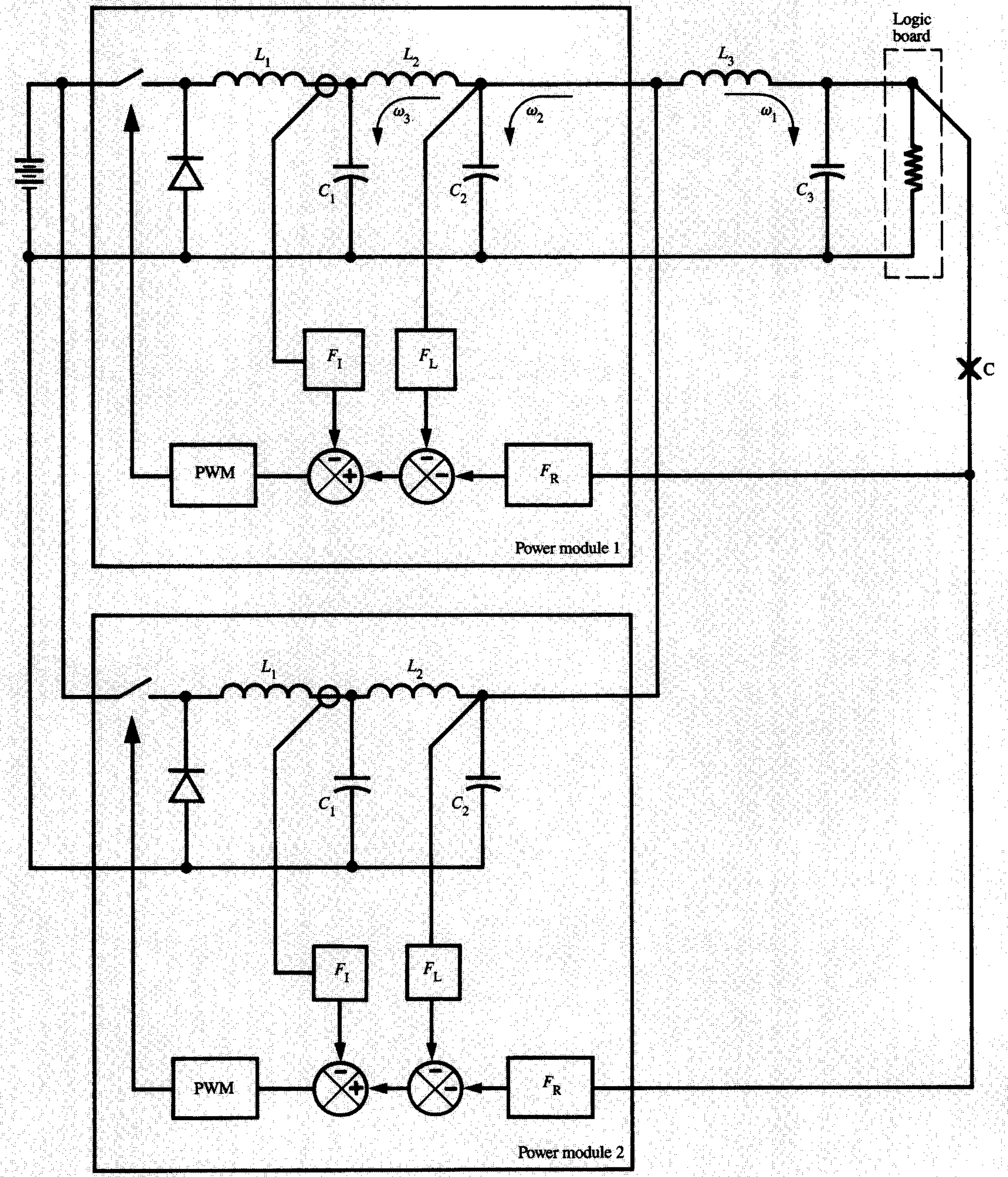


Figure 2

Power supply modules with three-loop feedback control.

Implementation of current sharing

The control circuit of each power supply must perform two critical tasks: It must 1) regulate the power bus voltage under steady-state and dynamic conditions and 2) uniformly adjust the average output current from each supply to achieve the shortest possible failure response.

All current-sharing methods used with parallel power supplies, with one exception, necessitate communication among supplies. Typically, a single-wire control line connected to each supply actively programs equal individual output currents. Excellent current sharing is achieved in these systems even when the individual voltage references are not well matched and special adjustments are not made to the reference voltages. However, steps to prevent a control line failure from causing loss of bus voltage add significant complexity to the controls and require transfer of control from one supply to another, which can result in inadequate fault recovery.

A passive current-sharing method was selected for the ES/9000 processors which does not require intersupply communication. This approach is naturally fault-tolerant, since interconnections that can fail are eliminated. Current sharing is not disrupted by the failure of an individual supply because each supply is independent. The disadvantage in using this method is that the output voltage of each supply must be tightly controlled, and the individual voltage references require factory adjustment.

Current sharing is established by programming the low-frequency output impedance of each supply to be significantly higher than is normal for conventional voltage regulators. Because each supply is current-mode controlled, the error voltage is proportional to its output current. By limiting the low-frequency gain of the error amplifier, a controlled "droop" is introduced into the dc voltage regulation of each supply that causes the output voltage to decrease in proportion to increases in the supply output current.

Because of the tight regulation required by the logic, the effective impedance used by each supply is less than 50 $\mu\Omega$, which results in less than 20 mV of regulation over the full load range. The individual supply currents are equal if their reference voltages are equal, since each power supply is now effectively connected to the power bus through a controlled resistance. In practice, current is uniformly shared between supplies to within 10% by selecting only low temperature-drift components and eliminating the initial differences between references.

Three-loop control circuit

As shown in Figure 2, three-loop feedback control is obtained by introducing a third controller, F_L, into each power supply module to sense the output voltage of the supplies. The sum of the output voltages obtained from F_L and F_R yields an error signal which, when compared with the current feedback signal at the pulse-width modulator (PWM), sets the duty cycle of the switching transistors. Thus, a new inner voltage loop is formed which is defined as the local-voltage feedback, while the original outer voltage loop is defined as remote-voltage feedback. The implementation of the three control loops in a power supply is illustrated in **Figure 3**. The heart of the control circuit is the error amplifier, which compares the bus voltage to a fixed reference and integrates the difference to generate an error signal in the remote-voltage feedback loop. The resistor across the error amplifier determines the low-frequency power supply output impedance by limiting the dc error amplifier gain.

The inductor voltage and the switching transistor current, which is proportional to the dc current level in L_1, are both sensed. Only the ac component of the inductor current is recovered when the inductor voltage is integrated with the error amplifier. This is an improved form of current-mode control which enhances small-signal performance [5, 6]. For high-current, low-voltage power supplies, a very low small-signal output is detected with conventional current feedback because the detected output signal is dominated by the dc inductor current signal. The signal derived from the inductor voltage (ac current feedback) provides high current-loop gain that would otherwise require a very high dc level of the transistor current feedback signal.

For three-loop control, the third feedback loop senses the local voltage at the power supply output. This voltage is summed with the remote-voltage feedback. The combined ac/dc current feedback yields a single control signal that determines the switch transistor duty cycle.

- *Small-signal analysis*

The relationship between a small-signal analysis of a three-loop-controlled power system and its closed-loop performance is considered for a power system that consists of six 3.6-V 450-A power supplies which provide a 2000-A logic load current. The fault-tolerant requirements of the power system are satisfied, since five power supplies can supply the total load current.

The six-supply system is analyzed by reducing it to an equivalent single power supply, using techniques discussed in [5]. This reduction contributes insight into the interaction among the three loops that is not apparent from a multi-supply system. Only the remote-voltage loop gain can be measured in a multi-supply system, since that loop is common for each supply, illustrated as point C in Figure 2. The equivalent system loop gains for the two inner feedback loops cannot be determined, since they are separate for each supply and no common measurement point exists.

The small-signal block diagram for the equivalent single supply is shown in **Figure 4**. The small-signal components of remote voltage, local voltage, and inductor current are represented as v_R, v_L, and i_L, respectively. The control variable, d, which is the small-signal component of the duty cycle, is derived from the summation of the three feedback signals. The transfer function blocks are defined

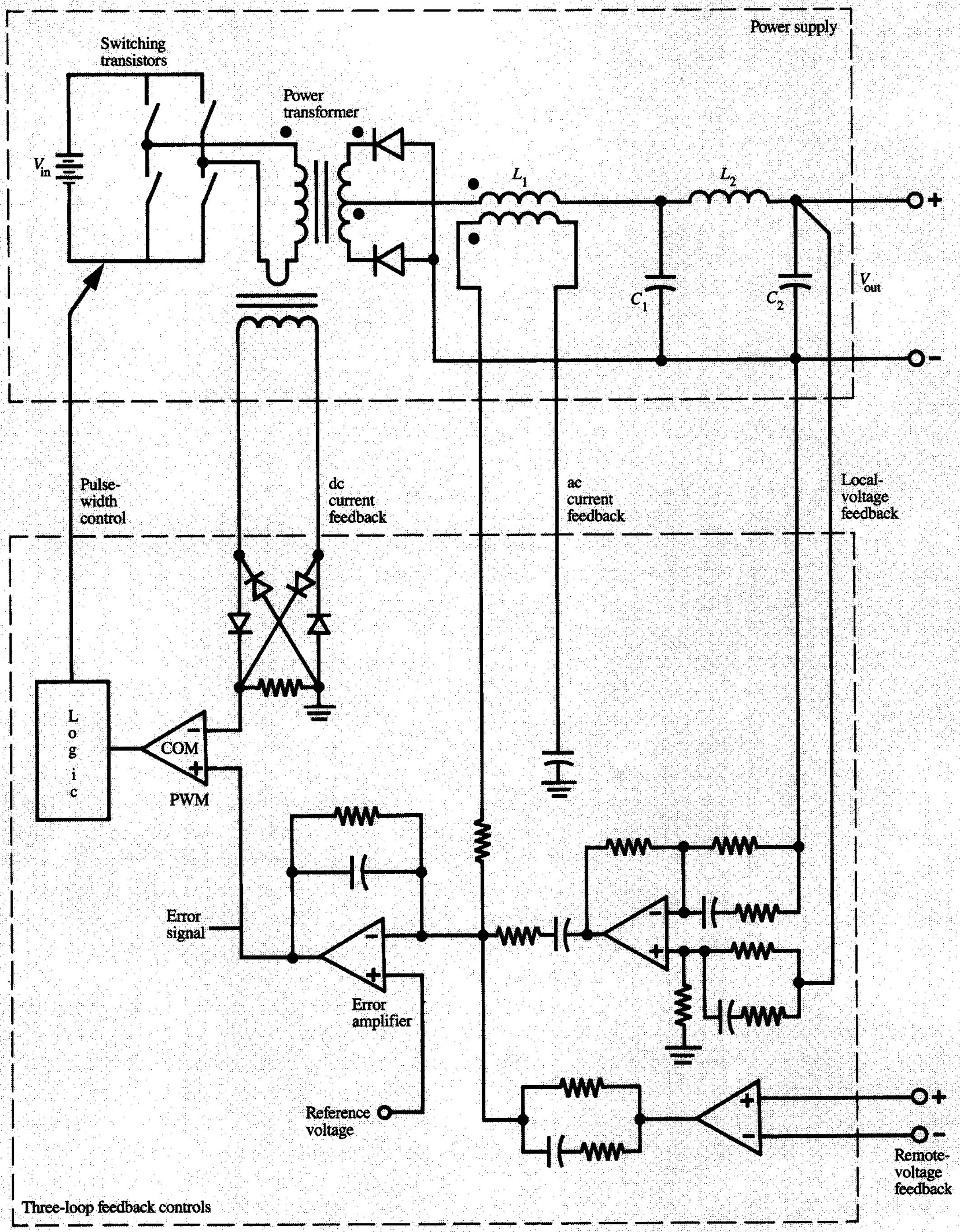


Figure 3

$N + 1 = 2$ redundant power supply configuration with three-loop control.

as follows: F_M = pulse-width-modulator gain, F_1 = control-to-remote voltage transfer function, F_2 = control-to-local voltage transfer function, F_3 = control-to-inductor current transfer function, F_I = current sense gain, F_L =

local-voltage loop controller, and F_R = remote-voltage loop controller.

The three feedback loops that form the current loop T_I, the local loop T_L, and the remote loop T_R are associated with the three feedback signals. Inspection of the diagram in Figure 4 shows that each loop can be expressed in terms of the various transfer function blocks as follows:

$$T_I \text{ (current loop)} = F_M F_3 F_I\,, \tag{4}$$

$$T_L \text{ (local loop)} = F_M F_2 F_L\,, \tag{5}$$

$$T_R \text{ (remote loop)} = F_M F_1 F_R\,. \tag{6}$$

The loop gains of a power supply are important parameters for designing system closed-loop performance requirements [7]. The loop gains that directly relate to system performance are the closed-loop gains measured at points A, B, and C in Figure 4, defined as the overall loop gain T_1, the middle-loop gain T_2, and the outer-loop gain T_3, respectively. These closed-loop gains are described in terms of the three feedback loops as shown below [8]:

$$T_1 \text{ (overall loop gain)} = T_I + T_L + T_R\,, \tag{7}$$

$$T_2 \text{ (middle-loop gain)} = \frac{T_L + T_R}{1 + T_I}\,, \tag{8}$$

$$T_3 \text{ (outer-loop gain)} = \frac{T_R}{1 + T_I + T_L}\,. \tag{9}$$

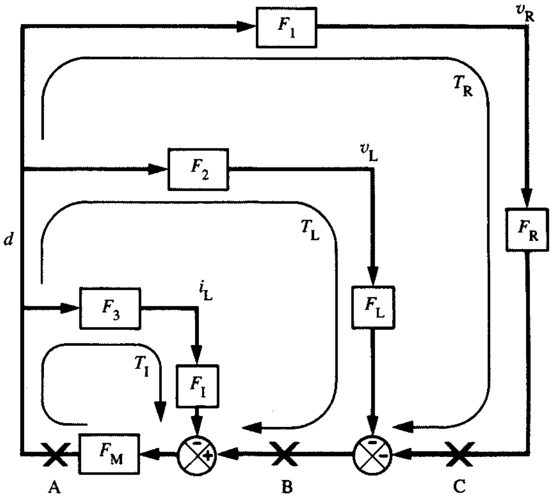
Each of these closed-loop gains, T_1, T_2, and T_3, is an important characteristic of the closed-loop performance of a power supply feedback control system. T_1 directly attenuates the response of the power system to input voltage disturbances, and T_3 attenuates its response to output current disturbances. The middle-loop gain, T_2, best illustrates the advantage of the three-loop feedback control system with respect to closed-loop performance.

- *Closed-loop performance*

The most important closed-loop characteristic for a redundant power system is its response to a sudden failure of an individual power supply. In the frequency domain, the supply-failure response is characterized by an impedance function that represents a change in output voltage due to a current disturbance injected at the summing junction of the power supplies. This transfer function is referred to as the transimpedance Z_t, to distinguish it from the more commonly known output impedance Z_o, which expresses the output voltage response to a load current disturbance [8].

The relationship between the middle-loop gain and transimpedance is illustrated in **Figure 5** for both two-loop and three-loop control. Two-loop control is simulated in the three-loop system by opening the local-voltage feedback loop T_L. In this figure, T_2 is shown with the open- and closed-loop transimpedance. The middle-loop gain directly attenuates the open-loop transimpedance (Z_{to}), since

$$Z_t = \frac{Z_{to}}{1 + T_2}\,. \tag{10}$$



$T_I = F_M F_3 F_I$

$T_L = F_M F_2 F_L$

$T_R = F_M F_1 F_R$

Loop gain at A: $T_1 = T_I + T_L + T_R$

Loop gain at B: $T_2 = \dfrac{T_L + T_R}{1 + T_I}$

Loop gain at C: $T_3 = \dfrac{T_R}{1 + T_I + T_L}$

Figure 4

Small-signal block diagram of three-loop control.

The middle-loop gain results from the presence of the local loop, which senses the point at which the current disturbance is injected. With three-loop control there is no evidence of a peak in Z_t, whereas a large resonance peak is observed at 4 kHz for two-loop control. This resonance peak causes severe overshoot and ringing in the time domain of the control system response.

Since the magnitude of the middle-loop gain has fallen almost to unity (0 dB) at ω_2, the mid-frequency resonance, the performance of two-loop control is degraded. Equation (10) indicates that the power bus voltage is no longer under control of its feedback loop. Furthermore, the rate at

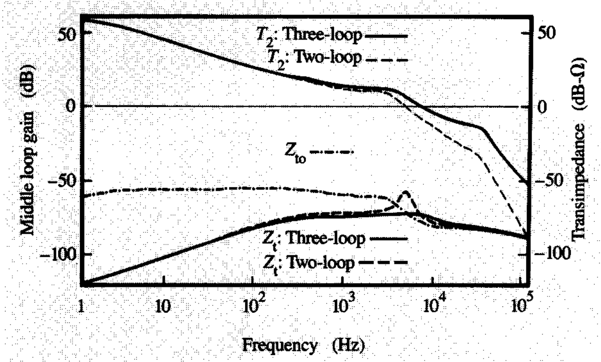


Figure 5

Middle loop gain (top two curves) and transimpedance (bottom three curves) for two-loop and three-loop control.

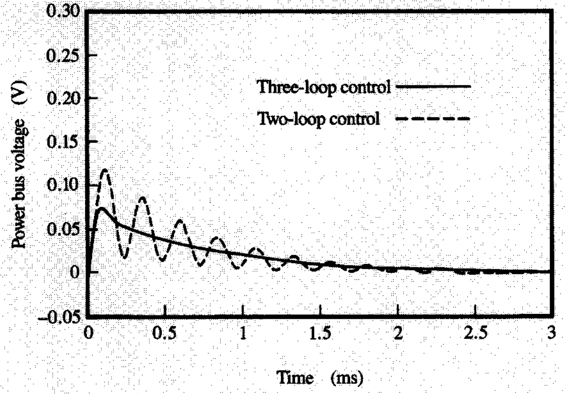


Figure 6

Supply-failure response: three-loop vs. two-loop control.

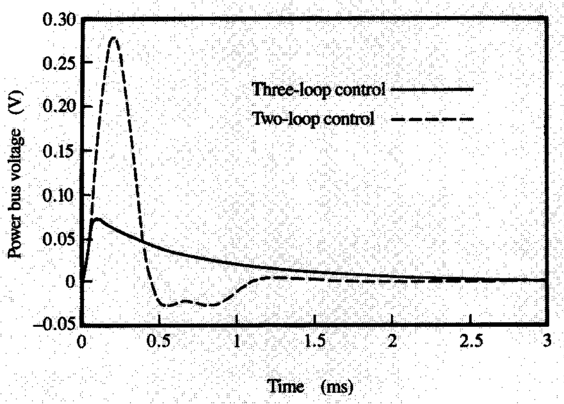


Figure 7

Supply-failure response: three-loop vs. two-loop control with reduced bandwidth.

which the magnitude of T_2 is decreasing indicates that the phase shift of T_2 is large, and its phase margin, the additional phase shift at which the loop response at the output is in phase with its input, resulting in positive feedback and instability, is small [9].

With three-loop control, the feedback information from the local loop extends the bandwidth of the middle-loop gain beyond ω_2 so that it can actively control the mid-frequency resonance. Since the slope of T_2 near unity gain is more gradual, the phase shift of T_2 is smaller, and stability of the control system response is ensured.

The output voltage disturbance generated when a power supply in an $N + 1$ configuration fails is directly predicted by Z_t. **Figure 6** shows the time domain representation of the transimpedance when a current step of 333 A appears following a sudden failure of one of the six supplies. The response for two-loop control is oscillatory, while the response for three-loop control is well damped, with a much lower peak amplitude. In fact, the two-loop system would most likely be unstable and would require compensation by reducing the bandwidth of the outer-loop gain to well below ω_2, the mid-band resonance. This is illustrated in **Figure 7**, which compares the supply-failure response of the compensated two-loop system to that of the three-loop system. The oscillations are eliminated, but the peak amplitude of the output voltage transient is 280 mV, as compared to 74 mV for three-loop control. These large-signal predictions, derived from a small-signal model, are consistent with experimental measurements [10].

Summary

Fault-tolerant power systems in ES/9000 processors are composed of feedback-controlled, multiple-power-supply modules that deliver high load currents to low-voltage logic circuit boards. The load currents are shared equally (to within 10%) among those power supplies that are needed to satisfy the load requirements and one redundant supply. The current-sharing method employed does not require interconnections between the power supplies. This approach is naturally fault-tolerant, since current sharing is not disturbed by the failure of a supply. The voltage transient caused by a power supply module failure is minimized by requiring that all supplies contribute equally to the total load current.

A local-voltage feedback loop added to each power supply two-loop feedback control system improves the response to voltage transients that occur when a power supply fails. Resonances which limit the performance of a conventional two-loop feedback control system are suppressed with the three-loop control system. An analysis of the three-loop feedback control system is presented, and its application is illustrated for a typical power system composed of six power supplies. A new closed-loop transfer function called transimpedance is identified to characterize the system response to a failed power supply. Time-domain simulations illustrate the superiority of three-loop control over a conventional two-loop control.

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