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Classification of Auxiliary Circuit Schemes for Feeding Fast Load Transients in Switching Power Supplies

Zhenyu Shan, Student Member, IEEE, Chi K. Tse, Fellow, IEEE, and Siew-Chong Tan, Senior Member, IEEE

Abstract—This paper presents a systematic classification of auxiliary circuit schemes for feeding fast load transients in switching power converters. The classification is based on the types of the implementation methods, practical constraints and performance. In particular, auxiliary circuits are classified according to the ways in which they are connected with the power supplies and loads, as well as the choice of control methods. Designed as a shunt output, the “intruding” type of auxiliary circuits is effective and less dissipative. Moreover, to reduce complexity, auxiliary circuits may be designed in the form of a bridge output, and employs a “non-intruding” type of control scheme. Furthermore, provision of pre-informed loading condition leads to further simplification of auxiliary circuitry and improvement of efficiency. Experimental measurements are provided to support the analysis of the properties of various types of circuits.

Index Terms—Auxiliary circuit, classification, dc-dc converter, fast transient.

I. INTRODUCTION

Modern digital loads, such as microprocessors or digital signal processors (DSPs), impose challenging requirement for power supplies to feed high slew-rate transients [1], [2]. The main challenge in the power supply design is that after the occurrence of a transient, the power supply should keep its output voltage fluctuation within a short transition period and recover itself to a new operation point. If the converter can always keep its output voltage within a specified range around the reference point, e.g., ±2% of the reference value, the response of the power converter is said to produce a null-response to large-signal transients. The fundamental limitation for achieving null-response to large-signal transients is the size of the filter capacitor [3]–[5]. Many nonlinear control schemes, e.g., time optimal control [6]–[9], sliding-mode control [10], boundary control [11], [12], etc., have pushed the dynamic performance of a converter near to its physical limit.

To achieve further breakthrough without efficiency degradation, a number of methods utilizing auxiliary circuits have been proposed [3]–[5], [13]–[31]. Such auxiliary circuits operate as add-on current sources which will feed current with identical magnitude but in reverse direction to the transient to counteract the fast load change. An equivalent model of the auxiliary circuit is given in Fig. 1.

The use of auxiliary circuits has been proven effective for improving the dynamic response of the original converter. The increased complexity and efficiency reduction due to the use of the auxiliary circuit have been discussed for different practical situations. Specifically, the efficiency reduction has been studied previously in [5], [19], [25]. The problem of efficiency reduction in these schemes becomes significant because high-performance microprocessors operate with transients of huge magnitude and high repeating rate. To achieve optimal performance for specific applications, it is necessary to derive a common set of design principles for the application of auxiliary circuits. In this paper, we propose a way to classify the existing schemes of auxiliary circuits. Through the process of classification study, we hope to provide a systematic exposition of the design considerations of auxiliary circuits and to offer insights into the construction of suitable auxiliary circuits to satisfy specific requirements.

II. OVERVIEW OF CLASSIFICATION

The earliest auxiliary circuits are achieved by linear circuits that may be a linear voltage regulator or power transistor pair [13]–[16]. Resistance branches are added to create auxiliary cur-
In terms of connection style, auxiliary circuits can be classified into two categories, namely, the **shunt-output style** (or simply called **shunt style**)[13]–[20], [30], [33] and the **bridge-connection style** (or simply called **bridge style**)[3]–[5], [21]–[29], [31], [32], [34], [35], as shown in Fig. 2. For the shunt style, the auxiliary circuit is plugged on to the output port of the power supply and hence can be used in isolated power supplies. Moreover, the auxiliary circuit must include sufficient capacity of energy storage elements or independent power source. For the bridge style, the auxiliary circuit is connected across the input and output ports of the power supply.

In terms of interaction style of control loops, classification can be performed according to the way in which the control loop of the auxiliary circuit interacts with that of the main power converter. Specifically, we can classify auxiliary circuits as **intruding style**[3]–[5], [16], [17], [19], [20], [22]–[28], [30]–[32], [34], [35] or **non-intruding style**[13]–[15], [18], [21], [29], [33], depending on whether the control loop of the main converter would be interrupted or affected during the transient operation. In the intruding style, the auxiliary circuit control loop will affect the switching actions of the main converter, as shown in Fig. 3. Such auxiliary circuits can achieve the fastest change of the inductor current. On the other hand, in the non-intruding style, the auxiliary circuit does not interact with the main converter whose dynamics will be solely determined by its own feedback loop at all times. The auxiliary circuit effectively makes the original fast load transient appear as a slowly changing current slope that can be treated as a small-signal interference.

Recently, there has been rapid development in the availability of computer load information, resulting in a likely trend that the load profile including transient magnitude and time of occurrence can be accurately provided. Specifically, microprocessors, loads with fast transients, can predict the energy requirement and time of code executions quite accurately[36]–[41]. A paradigm shift in power supply design may therefore be conceived that the design of power converters may make use of the advance information about load changes [30], [31]. The impact of this paradigm shift on the design of auxiliary circuits is that communication is possible between the load and the auxiliary circuit, and hence load changes are no longer necessarily regarded as random or unpredictable processes. Thus, the load may pre-inform the auxiliary circuit before it steps up or down such that the switching frequency of the auxiliary circuit can be changed to avoid unwanted delays in transient detections. We refer to this type of auxiliary circuits as **load-informed style** as given in Fig. 4 and to others as **non-load-informed style**.

In the next section, we make a comparison of the **shunt-output** and the **bridge-connection** schemes. In Section IV, the development trend and implementations of the **intruding** scheme are discussed. In Section V, the pros and cons of the **load-informed** auxiliary circuit schemes are discussed. Finally, in Section VI, we present some experimental measurements based on a buck converter to validate the various comparative properties under the proposed classification schemes.
III. SHUNT-OUTPUT AND BRIDGE-CONNECTION AUXILIARY CIRCUITS

A. Power Loss

For the sake of comparison, we employ the bi-directional buck-boost converter as the auxiliary circuit for both shunt and bridge styles, as given in Fig. 5. Without the connection to $V_s$, the auxiliary circuit belongs to the shunt style. Here, $V_{as}$ varies according to the choice of circuit parameters and the operation of the circuit [19]. Moreover, with the connection to $V_s$, the circuit assumes the bridge style and $V_{as}$ becomes a constant.

The conduction power loss, switching loss and driver loss [27], [42] in the auxiliary circuit can be expressed mathematically as respectively

$$P_{\text{con.loss}} = \frac{I_{\text{step}}^2 + I_{av}^2}{12} \{R_{\text{on}} + R_1\},$$

$$P_{\text{sw.loss}} = P_{\text{sw.on}} + P_{\text{sw.off}}$$

$$P_{\text{sw.on}} = \frac{2}{3} C_{\text{oss}} V_{as}^2 f_s$$

$$P_{\text{sw.off}} = \frac{1}{4} V_{as} I_{\text{step}} f_s f_s$$

The meaning of the variables are explained in Table I. Here, (1) indicates that the conduction loss is independent of $V_{as}$. From (2) and (3), it can be observed that for the required $I_{\text{step}}$ and the given components, the switching and driving losses mainly depend on $V_{as}$ and $f_s$.

When the auxiliary circuit is operating for a negative transient (i.e., step-down load current), $T_{\text{on}}$ is operating as an active switch, as shown in Fig. 6. Usually, $m_1$ (the slope of the falling edge), $m_3$ (the slope of mean $i_a$) and $I_{av}$ are specified by the application. It can be observed that $f_s$ depends on $V_{as}$, i.e.,

$$m_3 = \frac{I_{\text{step}}}{T_{\text{on}}} = m_3 (1 - L_1) - m_1 D_1$$

$$= \frac{V_{as} m_3}{V_o} \frac{(V_{as} - V_o)}{V_{as} - V_o},$$

$$D_1 = \frac{m_1 (V_{as} - V_o)}{m_1 V_{as}},$$

$$\approx 1 - \frac{V_o}{V_{as}} (m_1 \gg m_3)$$

and

$$f_s = \frac{D_1}{T_{\text{on}}} \approx \frac{1}{T_{\text{on}}} \left(1 - \frac{V_o}{V_{as}}\right)$$

where $T_{\text{on}}$ is a function of $m_1$, $m_3$ and $I_{av}$. Substituting $f_s$ in (2) and (3) by (6), the sum of switching power loss and driver loss can be found as

$$P_{\text{sw.loss}} + P_{\text{gcd.loss}} = \frac{2}{3} C_{\text{oss}} V_{as} (V_{as} - V_o)$$

$$+ \frac{1}{4} I_{\text{step}} f_s (V_{as} - V_o)$$

$$+ C_{\text{iss}} V_{gs}^2 \left(1 - \frac{V_o}{V_{as}}\right) \frac{1}{T_{\text{on}}}. \quad (7)$$

From the above equations, we clearly see that decreasing $V_{as}$ will substantially reduce power loss.
Fig. 6. Operation under negative load transient, i.e., step-down load current.

The scenario of positive transient, i.e., step-up load current, is shown in Fig. 7. The power loss can be calculated in a likewise manner as for the case of negative transient above, i.e.,

\[ m_d = \frac{i_{\text{step}}}{T_{\text{tran}}} = m_1 D_1 - m_2 (1 - D_1) \]
\[ = \frac{m_1 V_o}{(V_{as} - V_i)} - \frac{m_1 D_1 V_{as}}{(V_{as} - V_o)} \]
\[ D_1 = \frac{m_1 V_o - m_3}{m_1 V_{as}} \]
\[ \approx \frac{V_o}{V_{as}} (m_1 \gg m_3) \]
\[ f_s = \left( \frac{D_1}{T_{\text{on}}} \right) \approx \frac{V_o}{T_{\text{on}} V_{as}} \] (8) (9) (10)

And finally, we get

\[ P_{w, \text{loss}} + P_{g, \text{loss}} = \frac{2 C_{\text{loss}}}{3 T_{\text{on}}} V_{as} V_o + \frac{1}{4} L_{\text{res}} t_f \frac{V_o}{T_{\text{on}}} + C_{\text{loss}} V_{gs}^2 \frac{V_o}{T_{\text{on}} V_{as}} \] (11)

In this case, the minimal value of \( P_{w, \text{loss}} + P_{g, \text{loss}} \) exists while \( V_{as} = \sqrt{3C_{\text{loss}}/2C_{\text{loss}}V_o} \). Since \( C_{\text{loss}} \) is usually a few times of \( C_{\text{loss}} \) and \( V_{gs} \) is 8 to 12 V for low \( V_o \) applications, variation in \( V_{as} \) will not quite affect (11), as compared to (7). Fig. 8 shows a plot of the total power loss versus \( V_{as} \).

B. Choice of Applications

When the converter is operating at a high input-to-output ratio, e.g., \( V_i/V_o = 12/2.5V/V \). The auxiliary circuit only need to work for negative transients [25]. When the bridge-connection scheme is chosen, the auxiliary circuit will incur a high dissipation. This is because \( V_{as} \) is fixed and has the same voltage as \( V_i \). However, when the shunt scheme is applied, \( V_{as} \) will be provided by \( C_o \) and controlled by configuring the capacitance. In this case, a strategy for energy balance is necessary, and can be achieved by reservoir capacitor voltage control, which will incur power loss [19]. If this power loss is sufficiently small, the shunt scheme will still be more desirable.

On the other hand, when the converter is operating at a low input-to-output ratio, e.g., \( V_i/V_o = 5/2V/V \). The power loss of the circuit in the bridge-connection scheme will be naturally reduced. Thus, the simpler bridge scheme is preferred.

Moreover, when isolation is required between the input and output, the shunt scheme will be the only choice.

IV. NON-INTRUDING AND INTRUDING AUXILIARY CIRCUIT SCHEMES

The purpose of using an auxiliary circuit is to make a large load fast transient “appear” as a slow transient load current so that any ordinary power supply would be able to handle the load change. Effectively, the auxiliary circuit and the load together present themselves as a composite smart load (whose transients are always slow) to the power supply. When the resulting slope of the transiting current is relatively high, the operation time required of the auxiliary circuit is relatively short, as shown in Fig. 9. The intruding scheme provides the shortest operation.
Fig. 9. Operation time of the auxiliary circuit depends on the current slope of \( i_a \) but is limited by \( k_T \).

Fig. 10. Non-intruding auxiliary circuit schemes are achieved by a closed-loop main converter and an open-loop auxiliary circuit.

A. Non-Intruding Schemes

Suppose the application of the auxiliary circuit makes the resulting load current change slowly, i.e., a relatively long \( T_{\text{trans}} \). The resulting current thus becomes a small perturbation having most frequency components lying within the bandwidth of the control loop of the main converter. In this case, \( v_c \) can be tightly regulated. In this operation, the programmed \( i_a \) is well tracked by the main converter, as illustrated in Fig. 10.

The auxiliary circuit does not interact with the control loop of the main converter, and is referred to as a non-intruding auxiliary circuit scheme. The advantage is that two parts (main converter and auxiliary circuit) are almost operating independently. Using this scheme, an existing main converter might be enhanced in dynamic performance without modifications on its original circuit design to cater the scheme.

The simulation result is given in Fig. 11, where the main converter takes 5000 \( \mu \)s (100 switching cycles) to relocate its operation point. The application of non-intruding schemes obviously have their drawback as they may incur a higher power loss due to the prolonged active period \( T_{\text{trans}} \). Components with larger current and heat rating are thus needed. Hence, trade-off between size, efficiency and overshoot on \( v_c \) would need to be considered.

B. Intruding Schemes

To overcome the inherent deficiency of the non-intruding scheme, we need to shorten the active time, for example, by speeding up the rate of decline of \( i_a \). The shortest possible active time of \( i_a \) is \( T_{\text{trans}} \), as shown in Fig. 9. However, the main converter may fail to follow \( i_a \) for such a fast trajectory, as controllers cannot have infinite control bandwidth [43]. The solution is to let the auxiliary circuit interact with the control loop of the main converter to achieve the fastest transition while the auxiliary circuit is following the state of \( i_L \) to provide the required current. Auxiliary circuits that interact with the main control loop are referred to as intruding auxiliary circuits.

In the mechanism described in Fig. 12, there is a circuit block to identify the transient at \( i_a \), intruding a biasing signal to change the duty cycle of the main converter. This obviously will increase the complexity of the control system. Only a few additional low power components need to be included in the existing PWM controller ICs. In practice, there are two ways to achieve the intruding function in PWM controllers.

1) Brute-Force Switching of the Switch Signal: A multiplexer can be added to the switch controller of the main converter, as explained in Fig. 13. Normally, \( c_1 \) from the original feedback controller is enabled, while the auxiliary circuit is suspended. When an \( i_a \) transient is detected, \( c_2 \) from the auxiliary circuit is enabled to enforce a “100%” duty cycle for a positive transient or “0%” duty cycle for a negative transient. This method has been adopted in most auxiliary circuit schemes [17], [19], [20], [22], [24]–[27], [30].
2) Injecting a Feedforward Signal: Another way to achieve intruding is shown in Fig. 14, where a feedforward signal dependent on $i_L$ is injected to the feedback control through the network $Z_L$ [30], [31]. In a conventional linear controller, the control signal $v_c$ derived from $v_o$ cannot follow $i_L$ in the large-signal sense. When the feedforward signal is added to the feedback network, a fast transient at $i_L$ will lead to a large increment or decrement in $v_o$, which can achieve a “100%” or “0%” duty cycle instantly.

Injecting a feedforward signal has an extra merit. When the auxiliary circuit is active, the operating point is allowed to shift at a large scale in a short time. However, under a linear feedback controller, the operating point can only move slowly at small-signal scale. Thus, the feedback controller cannot take $v_o$ to the new steady-state point quickly enough following a rapid change in $i_L$. The feedforward signal not only switches the duty cycle to 1 or 0, but also pushes $v_o$ to the new operating point without any overshoot in $v_o$. Fig. 15 shows the comparison of the brute-force switch-signal switching and the use of feedforward signal. It is noted that at instants of 1.0 ms and 1.5 ms, the load transients and voltage deviations have been addressed by the auxiliary circuit.

In Fig. 15(b), the duty cycle is switched to “0” or “1” by brute-force switching. It is clear that $i_L$ initially is not tracked to $v_o$ as the control loop is temporarily suspended, and after the transition (active period of the auxiliary circuit), $i_L$ is re-tracked to $v_o$. In this process, a voltage deviation occurs. Moreover, in Fig. 15(c), $v_o$ is influenced by the feedforward signal, causing $i_L$ to react spontaneously during the transition.

V. LOAD-INFORMED AUXILIARY CIRCUITS

As explained in Section II, computer loads are capable of providing accurate load profile information, including the magnitudes and times of occurrence of load transients. Auxiliary circuits can thus be designed with the assumption of the availability of load information. Essentially, the load communicates with the auxiliary circuit about a future occurrence of a load transient, allowing the auxiliary circuit to pre-charge its storage element appropriately and provide the necessary fast transient current at the time it occurs. This eliminates the limitation caused by sensing delays when the load transients occur at random times.

A. Benefits of Load-Informed Schemes

The first obvious advantage of the load-informed scheme is the elimination of transient sensing circuits[30], [31]. Voltage deviations due to the sensing delays can thus be avoided.

In the previously described non-load-informed auxiliary circuit using a switching power circuit, the design involves trade-off consideration between efficiency and output voltage deviation. In the scenario of Figs. 6 and 7, to provide faster $i_L$ to meet the high slew rate requirement, a small inductor should be employed, necessitating the use of a high switching frequency and incurring a high power dissipation.

With the load-informed auxiliary circuit, the load information including step time, magnitude and direction are known in advance. Thus, the auxiliary circuit can pre-energize its storage elements and to address the transient at the right synchronized
time [30]. The auxiliary circuit can thus be designed to achieve a higher current slew rate at a lower switching frequency.

B. Limitations of Load-Informed Schemes

The effectiveness of the load-informed scheme depends on the precision of loading prediction, and the effect of inaccurate load profile information remains fundamental. Since the loading prediction method of microprocessor or computer loads is based on execution models of the given codes, errors may be inevitable due to some unexpected events such as interrupts.

When the predicted magnitude of \( I_{\text{step}} \) has an error of \( i_{\text{err}} \), \( i_L \) may be adaptively regulated, as depicted in Fig. 16(a) for the intruding scheme, to make sure the two hatched triangles have identical area. In this case, a current sensor will indicate the real value of \( I_{\text{step}} \). Hence, \( i_L \) will not run beyond the needed scale. It is noted that this sensor does not require a wide bandwidth, while the active time of the auxiliary circuit is controlled by load information instead of transient detection. The voltage overshoot due to the inaccuracy of magnitude prediction can be estimated as

\[
\Delta V_{\text{ce}} < \frac{T_{\text{tr}} i_{\text{err}}}{4C_c}.
\]

For the non-intruding scheme, as shown in Fig. 16(b), \( i_L \) can track the scheduled trajectory and the converter is able to follow \( i_{\text{mon}} \). The voltage overshoot is caused by the main converter feeding a transient of \( i_{\text{err}} \). As long as the main converter can feed a small transient, i.e., \( i_{\text{err}} \), the scheme will allow a maximum prediction error of \( i_{\text{err}} \).

Furthermore, a sync signal indicating the time instant of a transient occurrence may be introduced to guarantee the synchronization of the action of the auxiliary circuit with the transient. Essentially, the auxiliary circuit may prepare itself with the received information, and the action of delivering \( i_L \) can be induced by the sync signal, as illustrated in Fig. 17. Therefore, an inaccurate prediction in the time of transient occurrence may be lumped on the magnitude error which can be handled readily.

VI. EXPERIMENTAL VALIDATION

A. Experimental Circuits

To validate the above analysis, two sets of experimental circuits are constructed. Fig. 18 shows the experimental circuit. A buck converter (parameters given in Table II) with an auxiliary circuit (parameters given in Table III) operating in a shunt-output style or bridge-connection style is implemented. The schematic diagram is given in Fig. 19.
The switch \( K \) is for selecting the operation mode between the \textit{shunt-output} style and the \textit{bridge-connection} style. When \( K \) is on, \( V_{in} \) is duplicated from \( V_i \), establishing a \textit{bridge-connection} scheme. Conversely, when \( K \) is off, a \textit{shunt-output} scheme is established. Here, \( V_{in} \) is controlled by the reservoir capacitor voltage \([19]\). For brevity, the function mode of the reservoir capacitor voltage control is not shown in Fig. 19. The dummy load is able to generate transients from 5 A to 10 A. The module \( M_1 \) is used to detect the transient at the load side and generate an indication pulse ("StepUp" and "StepDown"), whose pulse width is proportional to the amplitude of the transient. Also, \( i_c \) is measured from the value of \( dv_{dc} / dt \) by a differential circuit, and \( i_c \) is measured by a current sensor with current sensor amplifier ADM4073T.

Another buck converter (parameters given in Table IV) with an auxiliary circuit (parameters are same with Table III) operating in the \textit{intruding} style under the two implementation strategies described earlier is implemented. The schematic diagram is shown in Fig. 20. The transient detection and the control circuits are the same as the first prototype constructed for the \textit{shunt-output} scheme.

In the control circuit of the main converter, two functional blocks are employed to achieve the "intruding" scheme, which will facilitate generation of a fastest response under the two implementation approaches, namely, brute-force switching of the switch-signal and feedforwarding. The circuit serving the former is a multiplexer. When no transients occur, the channel 0 is selected and hence the traditional peak current control loop is formed. Either "StepUp" or "StepDown" signal is enabled, and the high-side switch is set as "1" or "0". The circuit serving for the latter is a bilateral switching resistors group, where bilateral switches are implemented by CD4066. When "StepUp" or "StepDown" is enabled, the corresponding switch will be turned on to vary \( v_{cc} \).

In these prototypes, the buck converter is controlled by a current-mode controller UC3843. A simple RC compensation network \((R = 2.7 \, k\Omega; C = 560 \, \mu\text{F})\) maintains stability in the main converter. To achieve the appropriate feedforwarding in \( v_{cc} \), two 15 k\( \Omega \) and 56 k\( \Omega \) resistors are employed. Hence, when the negative terminal of the error amplifier is connected to 0 V through the 15 k\( \Omega \) resistor, a 360\,mV/\( \mu\text{s} \) ramp-up is achieved. On the other case, when 5 V is connected through the 56 k\( \Omega \) resistor, a 961\,mV/\( \mu\text{s} \) ramp-down is achieved. The two implementations of the intruding scheme will be enabled separately.

### B. Power Loss Comparison of Shunt-Output and Bridge-Connection Schemes

When the load is undertaking a 5 A transient, the auxiliary circuit operates separately in the two schemes for different \( V_i \). Power loss in these two cases are compared and given in Fig. 21. All measured values in the plots represent power loss of the auxiliary circuit during its normalized active period, i.e., 9.4\,\mu\text{s} which is the active time of the auxiliary circuit for 5 A step-down transients. For the \textit{shunt-output} scheme, the energy loss in the reservoir capacitor voltage regulation is also included in
the total energy loss. Note that when $V_i$ is high, the auxiliary circuit is only active for step-down transients.

For the bridge-connection scheme, $V_{aux}$ is equal to $V_i$. Referring to Fig. 21, the loss in the bridge-connection scheme for step-down transients (line P3 in the figure) is close to the ideal loss (line P5), which displays a rising trend as $V_i$ increases. Furthermore, for the shunt-output scheme, with a fixed range of $V_{aux}$ (4 V to 6 V), the auxiliary circuit is always pumping around 2 W power. The ideal power loss can be estimated as around 1.75 W, as labeled as dotted line P5 in Fig. 21. The absorbed energy will be discharged to the output slowly with dissipation. Thus, the real current power loss is higher than the ideal value.

From Fig. 21, we see that when $V_i$ is around 6 V to 8 V, the power loss of the two schemes are very close. However, when $V_i$ is higher, the power loss of bridge-connection style becomes significantly larger than that of the shunt-output style. This result verifies the analysis presented in Section III-B.

When $V_i$ drops to 6~V, the auxiliary circuit should be made to work to handle a step-up transient. Operating for a step-up transient incurs a higher power loss in the shunt-output scheme than the bridge-connection scheme. The reason is two-fold. First, the requirement of balanced bidirectional charging of the reservoir capacitor (only for shunt-output scheme) will incur more energy loss. Second, in the bridge-connection scheme, a lower $V_i$ will reduce the energy loss in the auxiliary circuit for negative transients while the shunt-output scheme is still applying 4 to 6 V in $V_{aux}$, incurring a constant energy loss. In this case, when $V_i$ is lower than 6 V, the bridge-connection scheme is preferred.

The overall efficiency comparison of the two auxiliary circuit schemes with the conventional buck converter without the schemes is presented in Fig. 22. A load transient of 5 A to 10 A is repeated every 100 μs. The mean load current is 7.5 A. Compared to the shunt-connection scheme, the converter with the bridge-connection scheme achieves a higher efficiency when $V_i/V_o$ is larger. As we can see, the efficiency difference is 0.5% between the two schemes when $V_i = 12$ V. The efficiency degradation incurred by the scheme is around 1% when $V_i$ is from 7 V to 12 V.

C. Comparison of Intruding Auxiliary Circuits

For the purpose of testing, we apply step-up and step-down load transients of 5 A to a standard buck converter under current-mode control with and without an intruding auxiliary circuit. The transient waveforms of $v_o$ and $i_L$ of the regulated buck converter are shown in Fig. 23(a). A 160 mV fluctuation in $v_o$ has been observed at the instant of application of a 5 A step-down transient. Auxiliary circuits using the two mentioned intruding schemes (as given in Section IV-B) are implemented, and the measured waveforms are given in Fig. 23(c) to Fig. 23(f). A reduced voltage fluctuation in $v_o$ has been observed for these cases.

Moreover, when the intruding scheme is implemented by brute-force switching of the switch-signal, voltage overshoot can be suppressed only during the active period of the auxiliary circuit, but the switch control signal of the main PWM controller is still in the transition stage. Hence, a secondary transient occurs and is marked in Fig. 23(e), where the control signal $v_c$ and the current signal $i_{L}$ are highlighted to illustrate this mechanism.

On the other hand, for the implementation using the feedforward scheme, we observe from Fig. 23(f) that $v_c$ has been appropriately changed by the feedforward signal which results in $i_L$ moving to the new operation point with an expected amount of voltage fluctuation. Hence, the feedforward scheme is suitable for tackling fast load transients in converters under current-mode control.

We omit the experimental validation of the load-informed schemes in this paper, as a more detailed exposition will be provided in a separate future publication [44] and the experimental prototype would involve a substantially different setup in order to illustrate the advance provision of load information in such schemes.
VII. EXISTING CIRCUITS UNDER THE PROPOSED CLASSIFICATION

The systematic classification of auxiliary circuits presented above provides a convenient framework for comparison of various types of auxiliary circuits. Specifically, it would be useful for circuit designers in deciding on the use of a specific circuit style or control method if the various auxiliary circuits can be compared in terms of their efficiency, circuit and control complexity, possible applications, along with some existing implementations.
In Table V, we provide a tabular comparison of the auxiliary circuits categorized under the proposed classification, i.e., types of power devices, connection styles, control methods, and load information availability, and make specific reference to their efficiency, complexity and possible applications. Our aim is to provide circuit designers a practical guideline for selecting auxiliary circuits and control methods for their specific applications. For instance, if a simple low-cost method is needed to enhance the transient response of a power supply feeding a non-computer load, a bridge-connected linear current source with non-intruding control would be adequate. On the other hand, a connected-connected switching current source with an intruding control would be very desirable for a microprocessor load which needs high efficiency.

VIII. CONCLUSION

In the paper, we present a classification of auxiliary circuit schemes for tackling fast load transients in switching power supplies. We first consider the construction of auxiliary circuits in terms of the way in which they are connected to the load and the main power supply, and also the interaction of the auxiliary circuit and the control loop of the main converter. Furthermore, we consider a classification based on a new design paradigm which has emerged from the recent research in load profile prediction in computer and microprocessor loads. Under this new paradigm, auxiliary circuits may receive advance load information and hence are able to tackle the transients by appropriately pre-energizing themselves. A comparison of the characteristics of the various schemes are discussed. Our study provides practical design pathways for selecting the appropriate kinds of auxiliary circuits for the applications concerned.

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<th>Classification</th>
<th>Types</th>
<th>Power loss</th>
<th>Complexity</th>
<th>Applications (load conditions)</th>
<th>Existing implementations (references)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[3]–[5], [13]–[16], [29], [34], [35]</td>
</tr>
<tr>
<td>Power devices used</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[17]–[28], [30], [32], [33]</td>
</tr>
<tr>
<td>linear current source</td>
<td>relatively high, as given by $P_{\text{loss}} = (V_i - V_o)I_o$ or $P_{\text{loss}} = V_oI_o$</td>
<td>consists of transistors and resistors only</td>
<td>low transient current, low transient repetition rate, integrated on-chip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>switching current source</td>
<td>low, as given by Eqs. (11) and (7)</td>
<td>uses reactive elements</td>
<td>high transient current, high transient repetition rate, based on discrete parts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connection styles with the power supply and load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[13]–[20], [29], [30], [32], [34], [35]</td>
</tr>
<tr>
<td>bridge connection</td>
<td>$P_{\text{loss}} \propto V_i$ (step-down transients) depending on $V_i$</td>
<td>no energy storage elements needed</td>
<td>low $V_i/V_o$ ratio, non-isolation applications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>shunt connection</td>
<td>$P_{\text{loss}} \propto V_{os}$ (step-down transients) depending on $V_{os}$</td>
<td>uses energy storage elements or extra power supply</td>
<td>high $V_i/V_o$ ratio, energy storage isolation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control methods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[13]–[15], [18], [21], [29], [33]</td>
</tr>
<tr>
<td>non-intruding</td>
<td>$E_{\text{loss}} = P_{\text{loss}}T_{\text{trans}}$ referred to Fig. 9, high</td>
<td>no interactions between the main converter and the auxiliary circuit</td>
<td>existing main power supply not modifiable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>brute-force switching of switch signal</td>
<td>$E_{\text{loss}} = P_{\text{loss}}T_{\text{trans}}$ referred to Fig. 9, low</td>
<td>switches the switch driving signal when the circuit is operating, complex</td>
<td>main power supply of voltage mode control with modifiable switching</td>
<td></td>
<td></td>
</tr>
<tr>
<td>injecting feedforward signal</td>
<td>injects feedback signals to the feedback loop when the circuit is operating, complex</td>
<td></td>
<td>main power supply of current mode control with modifiable compensation loop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load information availability</td>
<td>available (load-informed)</td>
<td>not related to power loss; but may affect total cost of the system [31]</td>
<td>needs a load level prediction signal</td>
<td>computer or other intelligent loads with advance step change information</td>
<td></td>
</tr>
<tr>
<td>not available</td>
<td>needs a wide bandwidth current sensor</td>
<td>no limitations on the load</td>
<td></td>
<td>[3]–[5], [13]–[29], [32]–[35]</td>
<td></td>
</tr>
</tbody>
</table>


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