THE DESIGN OF A HIGH EFFICIENCY CATV TRUNK POWER SUPPLY

Frank R. Little Jr.

SCIENTIFIC-ATLANTA, INC.

ABSTRACT

The advent of new technologies in modern CATV distribution electronics has placed increased importance on the operation of the station power supply, especially in feedforward and parallel hybrid station configurations. This paper addresses some of the important areas recently researched by Scientific-Atlanta in the design of a new switching regulated D.C. station power supply which accommodates all possible station configurations and combinations of gain stage technologies. Power circuit topologies and control circuit implementations are compared, and discussion is given to the author's chosen implementation.

INTRODUCTION

System powering costs and reliability are areas of increasing concern to system operators today as they work to improve service to their customers as well as keep operational and maintenance costs at a minimum. CATV station power supply efficiency and reliability bear directly on these aspects of system performance. Just as improvements in amplifier technology such as hybridized feedforward and parallel hybrid gain stages have enabled enhanced system distortion and reliability performance, recent advances in semiconductor technology and linear control integrated circuits have contributed to the design of more efficient and reliable switching regulated power supplies.

Advanced technology is incorporated in the design of Scientific-Atlanta's trunk station power supply yielding higher efficiency, lower operating temperature, and increased power handling capability. The discussion that follows addresses the various concerns involved in the design of advanced switching regulated D.C. power supplies for CATV amplifier stations. It is the purpose of this discussion to shed light on an area of CATV distribution equipment that is often not adequately addressed.

TOPOLOGY CHOICES

The function of the station power supply is to convert the A.C. voltage at the station power input to a well regulated D.C. voltage suitable for use in powering the equipment inside the station. It also provides line isolation for safety and performance reasons. One of the earlier and simpler forms of this supply is the power transformer coupled linear series-pass regulator. Due to its simplicity and low cost this system is still commonly used, particularly in the feeder area of CATV distribution plant. However, the low efficiency and high heat generation of these units makes them less than an optimal solution, particularly where higher output currents are required.

Switching regulated power conversion offers the advantage of achieving greater efficiency in the conversion process, resulting in lower power consumption and less heat generation within the station housing. The two major approaches to switching power conversion for use in CATV stations differ basically in their means of achieving line isolation. Figure 1 (a) shows a power transformer coupled version of a buck-derived step-down switching regulator. Figure 1 (b) shows an "off-line" high frequency transformer coupled switching regulator.

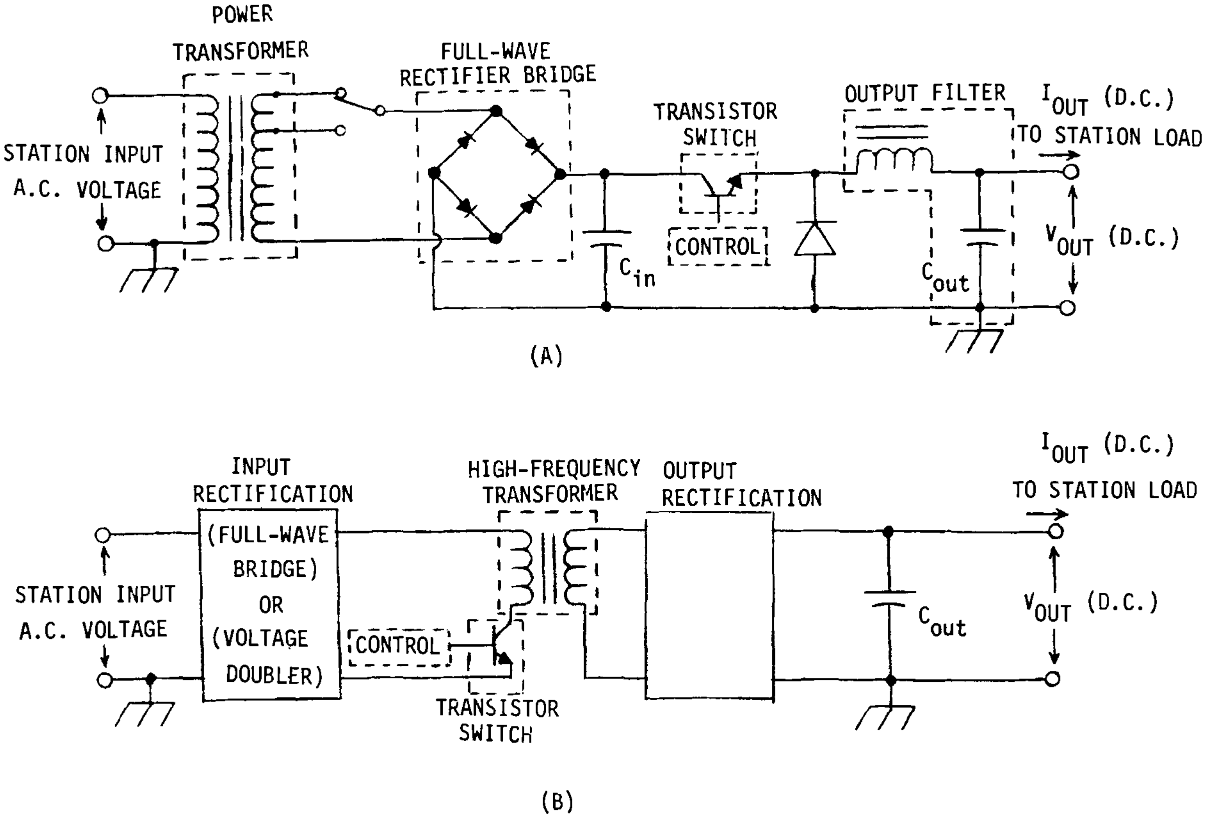

FIGURE 1

The general circuit topology shown in Figure 1 (a) provides line isolation through the use of a power transformer to couple the low frequency A.C. input to the station. This transformer breaks any complete direct current path between the input of the station and the output of the supply. A.C. input voltage is transformed to a chosen level by the transformer and supplied to the rectifier circuit which, in conjunction with an input capacitor converts this voltage to an unregulated D.C. voltage. The power switching circuitry produces a pulse train waveform from the unregulated D.C. input voltage at a predetermined frequency and filters the waveform to provide a fixed D.C. output voltage. The control method and components used to accomplish the power switching and filtering functions vary among designs, but the overall function is essentially the same. This particular aspect will be discussed in more detail later in this paper.

The general circuit topology shown in Figure 1 (b) provides line isolation through the use of a high frequency (in the tens of kilohertz range) transformer (or coupled inductor) in the D.C. to D.C. conversion stage. Designs based on this general architecture are often referred to as "off-line" or "transformerless" (although this is an inaccurate classification since almost all employ some type of transformer) because they rectify the A.C. voltage directly from the input line without a power transformer. The rectified voltage is chopped at a high frequency by the power switching circuitry and applied to the primary side of a high frequency transformer, which transforms the high frequency voltage waveform to a predetermined level at the secondary side. At this point the waveform is rectified and filtered, providing a regulated D.C. output voltage. In a version called the "Flyback", the transformer is used as an energy storage coupled inductor.

Both of these topologies essentially quantize the input power then filter and release this energy to the load at a well regulated and controlled voltage. Since this energy is merely transferred in a controlled manner as required from the input to the load, rather than dissipated as in the linear series regulator, the efficiency of these designs is much higher. Given today's state of the art in control system integrated circuits, power semiconductors, and other components, efficiencies at or above 80% can be attained in sophisticated designs which are derivatives of either of the general switching type topologies previously discussed.

For a given power output capability, the "off-line" type of topology can offer a size advantage over the power transformer coupled type. The higher frequency transformer which the "off-line" unit employs in the D.C. to D.C. conversion stage can be physically smaller than the line frequency transformer employed in the input stage of the power transformer coupled topology. The "off-line" type is also more easily implemented where multiple D.C. output voltages are required. These features have led to the increasing popularity of "off-line" designs in the general purpose (off the shelf) power supply and computer hardware power supply fields, where size, weight, and multiple output voltage capability are major concerns.

However, there are some concerns with using direct "off-line" rectification topologies in a CATV distribution plant station product. Without a transformer coupling to the input of the station, small diode imbalances and leakage currents in the electrolytic input capacitors can set up a small amount of D.C. current which flows through the coaxial cable. D.C. current flow can cause galvanic corrosion between dissimilar metal interfaces (i.e., splices, coax to housing connectors, etc.), especially in the presence of humidity.

This problem was prevalent in the early days of cable TV, where half-wave rectification was used without power transformer isolation. The large D.C. currents caused extensive corrosion problems. Although lab tests indicate the magnitude of D.C. current flow caused by direct full-wave rectification is relatively small, the long term effects of small, steady state D.C. current flow on cable plant remains to be seen. Connector reliability concerns, as well as signal ingress/egress associated with corroded "leaky" connector/cable ground interfaces, could pose significant problems for the system operators.

Another concern with "off-line" topologies lies in the need for special attention to input surge protection. The line frequency power transformer used in power transformer coupled topologies provides an inherently good measure of surge absorption and attenuation, particularly for the fast rise-time impulse and high frequency oscillatory high voltage waveforms associated with power grid switching transients and lightning strokes.

Because of the high reliability risk associated with galvanic corrosion and transient voltage protection and the need for maximum system reliability, we have chosen to pursue a new control method and component technology in the design of a trunk station switching power supply which retains the power transformer coupled topology.

A NEW DESIGN

With the development of feedforward amplifier modules, trunk station system configurations were re-evaluated to determine maximum D.C. current and power consumption figures which the station power supply would need to be capable of supplying in order to function in any station configuration. The maximum current configuration was determined to be that of a feedforward trunk amplifier, with feedforward bridging amplifier, dual hybrid reverse amplifier, automatic control module, and status monitor module. This configuration could require a maximum of 2.7 amps at 24 volts from the station D.C. power supply, with a nominal requirement of 2.5 amps. Other station configurations would require less D.C. current, but a 3 ampere output capability was chosen as the design goal which would allow for future module expansion.

As previously mentioned, the design chosen involves a transformer coupled switching regulated supply with an enhanced power transformer design and an improved D.C. to D.C. converter design. Figure 2 shows the

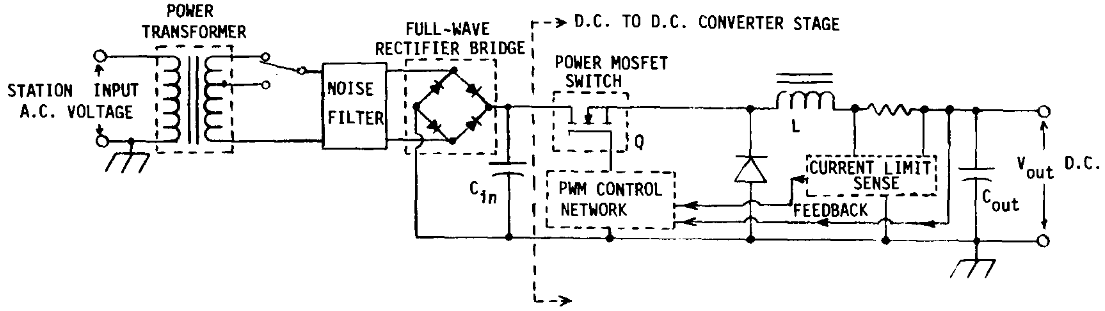

FIGURE 2

basic system diagram of the overall supply topology. In this topology, A.C. power is transformed from the input A.C. voltage level at the station to a selected A.C. voltage at the secondary (output) of the power transformer. It then passes through a common/differential mode noise filter to the input of a full wave bridge rectifier tied to the input capacitor of the D.C. to D.C. converter section. The power transformer performs a level shifting and isolation function and the noise filter attenuates any high frequency noise generated in the D.C. to D.C. converter which can be transmitted back through the transformer to the line. The full wave bridge rectifier gates the energy from each half cycle of the secondary A.C. waveform, applying it to the D.C. to D.C. converter input filter capacitor for storage and filtering. This provides an unregulated D.C. voltage to the D.C to D.C. converter.

This basic type of D.C. to D.C. conversion stage is generally referred to as a "buck" or step-down switching regulator. It efficiently converts a higher D.C. voltage to a lower D.C. voltage. Generally in this type of design, a pulse generator, controlled by a feedback loop from the supply output, pulses Q (the transistor switch) between full on (saturated) and off states to transfer energy from the input filter capacitor to the output filter elements L and C which act as an averaging filter, converting the pulses from Q into a D.C. voltage. To an approximation the relationship between input and output voltage can be expressed by:

$$E_{out} = \frac{t_{on}}{t_{on} + t_{off}} E_{in} \qquad (1)$$

where: t_{on} = on time of transistor switch Q
t_{off} = off time of transistor switch Q
$(t_{on} + t_{off})$ = switch period
= 1/switching frequency

Earlier CATV station power supply designs used a simple control circuit which held t_{on} relatively constant. As a result, output voltage could only be maintained constant vs. input voltage variations through a change in T_{off}, resulting in a change in switching period ($T_{on} + T_{off}$), and thus changing the switching frequency. This type of control is known as frequency modulation.

However, there are disadvantages to this control method. The broad range of frequencies the supply can assume during line input, load, and temperature variations makes it difficult to filter noise and shield the electromagnetic interference generated by the supply. The output filter elements are difficult to optimize for effectiveness and efficiency since they can't be designed around optimal performance for any set frequency. Lastly, in this topology the switching losses in the switching transistor can be expressed as:

$$P_S = V_{in} \text{ (D.C.) x } I_o \frac{t_r + t_f}{2(t_{on} + t_{off})} \qquad (2)$$

where t_r and t_f = rise and fall time (turn on and turn off time of switch transistor).

For every factor of two change in frequency (and thus switching period) the switching losses in the switching transistor can increase or decrease by a factor of 2. This in turn affects the overall efficiency of the unit.

Pulse width modulation control allows a switching regulator to operate at a fixed frequency, alleviating the drawbacks of the frequency modulation control technique. Fixed frequency operation allows more optimized component design and use, thus leading to higher efficiency and greater reliability. This method of control was chosen for implementation in the D.C. to D.C. converter stage of this design.

In a pulse width modulation (PWM) control design the switching period (t_{on} + t_{off}) remains constant (constant frequency operation). The on time (t_{on}) of the switching transistor (Q) in Figure 2 is varied in relation to changes in input line voltage. This varies the width of each pulse in the pulse train waveform supplied to the output averaging filter. This maintains the proper energy flow to hold the output voltage constant. This is expressed in Equation (1) with $t_{on} + t_{off}$ = constant. With constant frequency operation, the switching losses in the switching transistor vary less than with frequency modulation control. As shown in Equation (2) for a given D.C. output current switching losses vary only with input voltage since $t_{on} + t_{off}$ = constant.

Another advantage of pulse width modulation control is the ability to incorporate true pulse by pulse current limiting with output current foldback into the control network. In response to the magnitude of overload at the regulator output the on time (t_{on}) of the switching transistor is decreased, until under maximum overload at the output (a short circuit), the on time is decreased to its minimum value. This decreases the power dissipation in the switching transistor thus enabling the regulator to operate indefinitely in that mode without damage.

Recent advances in MOS technology have increased the performance of power MOSFET transistors. Power MOSFET transistors can be switched between full on (saturation) and off in less time than most power bipolar transistors, resulting in lower switching losses. As illustrated in Equation (2) when t_r and t_f decrease, the switching loss P_s decreases. In this design, two power MOSFET transistors were connected in parallel to produce a more power efficient transistor switch.

The use of power MOSFET switching devices and pulse width modulation control enabled the design of the D.C. to D.C. converter stage of the supply to be optimized for fixed frequency operation at a higher switching frequency than previous designs while keeping switching losses low. This allowed a reduction in the size of output filter components as well as an optimization of their D.C. and A.C. characteristics to increase their effectiveness and efficiency at the switching frequency. Overall, the physical size of the D.C. to D.C. converter stage was reduced by 30 percent.

PERFORMANCE RESULTS

The implementation of the advanced control method and component technology discussed, within the power transformer coupled switching regulator topology chosen, yielded practical performance improvements over previous designs. The typical operating efficiency of the new design was increased ten percentage points over its predecessor, and output power capability was increased over fifty percent.

Due to increased efficiency, actual power loss (dissipation) within the supply was reduced when compared with previous designs operated at comparable output voltage and current levels. The reduced dissipation resulted in lower internal ambient and component temperatures within the supply, as installed in the trunk station, when compared with previous designs powering the same station configurations (i.e. loads).

This new design has been operating in CATV systems in the field for 2 years without any significant reported failures or operational problems.

SUMMARY

Advances in the development of new power conversion components by power semiconductor, magnetic materials, and integrated circuit manufacturers have made improvements to switching regulated power supply performance possible. Refinements to newly developed technologies such as current-mode control and series resonant sine wave conversion hold promise for future size and cost reduction beyond what has been accomplished to date.

It is evident from the discussion presented that through careful application of advanced component technology and control methods to proven design topologies, dramatic improvements in CATV station power supply efficiency and thermal reliability can be achieved. The use of reliable, higher efficiency station power supplies can improve the performance of CATV distribution systems, by reducing overall system power consumption without affecting signal quality.

The CATV industry was built on the ideal of using advanced technology to provide a valuable product and quality service to its customers. As the industry matures, system operators must carefully evaluate the impact of equipment performance and reliability on system operation, in order to enhance their ability to provide the quality of service the customer demands.

ACKNOWLEDGEMENTS

The author would like to thank Rezin Pidgeon and Alan Schlenz of Scientific-Atlanta, Inc. and James Godwin for their technical research and suggestions in the development of the design discussed.

REFERENCES

1. Unitrode Power Supply Design Seminar Manual, Unitrode Corporation, 1985
2. Unitrode Applications Handbook, Unitrode Corporation, 1985-1986.
3. Owen J. McCaughey and Gaylord G. Rogeness, "Destructive Corrosion in CATV Distribution System Equipment", NCTA Technical Papers, 1973, pp. 53-71.
4. Motorola Power MOSFET Seminar Manual, Motorola Inc., 1984
5. RCA Power MOSFET Seminar Manual, RCA Inc., 1984
6. Unitrode Power Conversion Design Guide, Unitrode Corporation, 1984.