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Application Note

COMMUTATING FILTER TECHNIQUES

Prepared by
Bud Broeker
Applications Engineering

This note describes the design and construction of commutating (digital) filters using Motorola MECL II, MTTL III and MC7400 digital integrated circuits. A short section on commutating filter theory is included along with examples of filters and their responses.

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COMMUTATING FILTER TECHNIQUES

INTRODUCTION

Conventional filter synthesis often leads to physically impractical designs when low frequency, high Q, bandpass filters are required. While not a panacea, commutating filters offer an attractive alternative for such system requirements. Commutating filters also provide excellent temperature stability since the center frequency is dependent only on an external clock frequency. Any component variations, except in the clock, will affect the shape of the response but will not affect the resonant frequency. The resonant frequency can be varied from a few Hertz to several megahertz, thereby generating a tunable bandpass filter with constant bandwidth. The bandwidth is also variable by changing the number of sections commutated. These latter properties lead to many applications in the fields of both instrumentation and communication.

The fundamental operation of a commutating filter is based on switching between N identical low-pass filter sections at a clock rate N times the desired center frequency. This switching has the effect of reflecting the low-pass response about the commutating frequency, thereby generating a bandpass response. The bandwidth of the filter shown in Figure 1 is 2/N times the bandwidth of the original low-pass sections which is equivalent to reflecting a low-pass section with 1/N times the original bandwidth. The commutating filter also has passbands centered at 0 Hertz and at harmonics of the commutating frequency, but these responses are generally of lesser interest.

COMMUTATING FILTER THEORY

The operation of the commutating filter is most easily understood by considering the simple low-pass section of Figure 2 as an integrator with time constant $\tau = RC$. If we cascade N of these sections with a commutating switch, as shown in Figure 3, we have a commutating filter. The commutating switch rotates at f_c rotations per second. Since each capacitor is connected to the input for only 1/Nth of the time, its time constant is increased by N to $\tau' = NRC$. The time constant of the cascaded group is also $\tau' = NRC$, yielding a 3 dB lowpass response of $f_{LP} = 1/2\pi NRC$. The output of this commutated lowpass filter is in step format where each capacitor charges toward the average voltage applied for its 1/Nth segment of the input signal.

If a signal at the commutating frequency, f_c, is applied to the filter, an individual capacitor sees the same average voltage each time it is switched into the circuit. The capacitors thus "see" a stationary signal and quickly charge to the average voltage seen. As the individual capacitor segments are sequenced by the commutator, a step format reproduction of the original signal is derived. Figure 4 shows such an input signal and the derived step format output. Once the capacitor sections have charged to the applied voltages, there is little attenuation of the incoming signal, with this attenuation being dependent only on the number of sections and on loading. A signal separated from the resonant frequency by f_s Hertz (i.e. $f_c - f_s$ or $f_c + f_s$) appears the same as f_s to the low-pass sections,

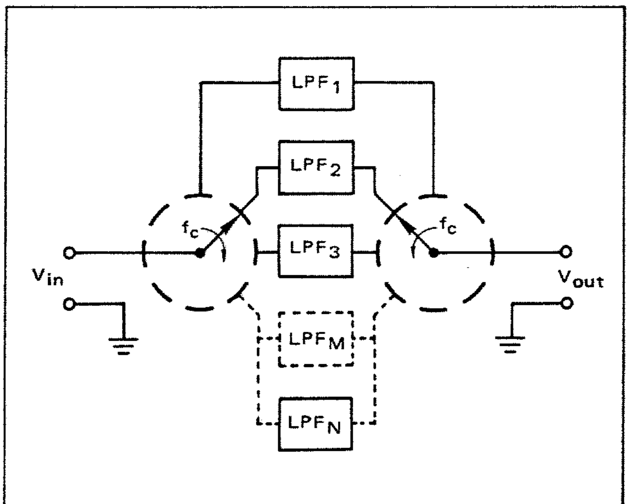


FIGURE 1 – N-Section Commutating Filter

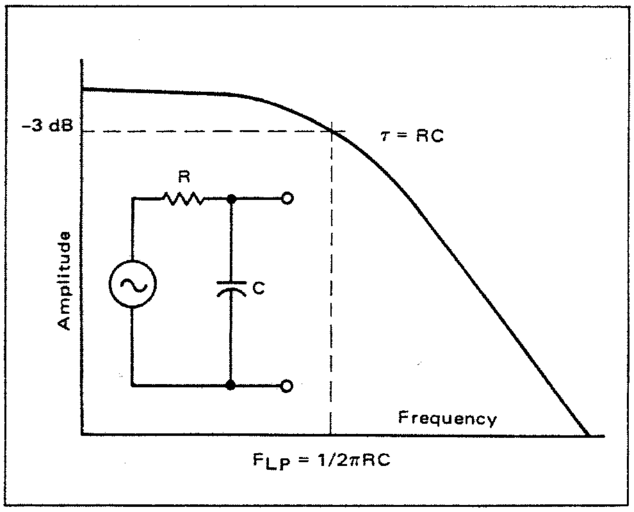


FIGURE 2 – Simple Low-Pass Section

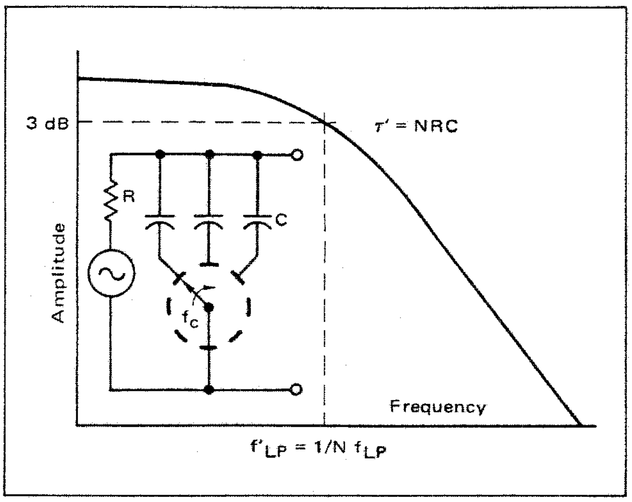


FIGURE 3 – Commutated Low-Pass Filter

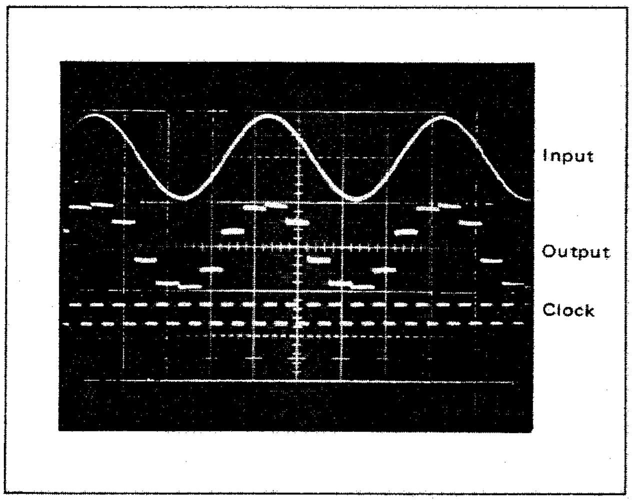


FIGURE 4 – Oscilloscope Trace of Commutating Filter Waveforms

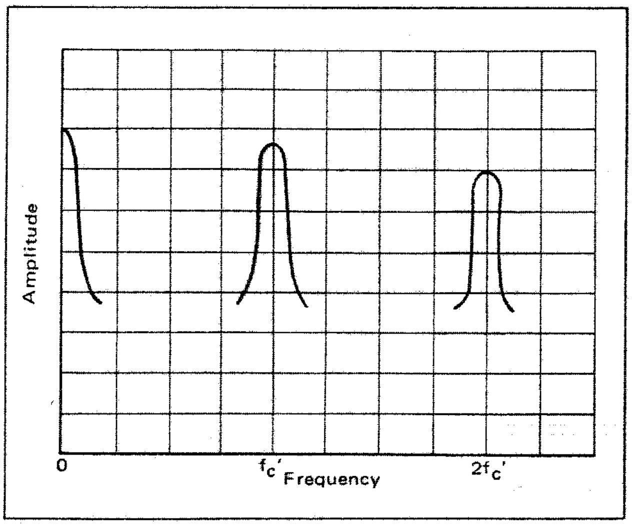


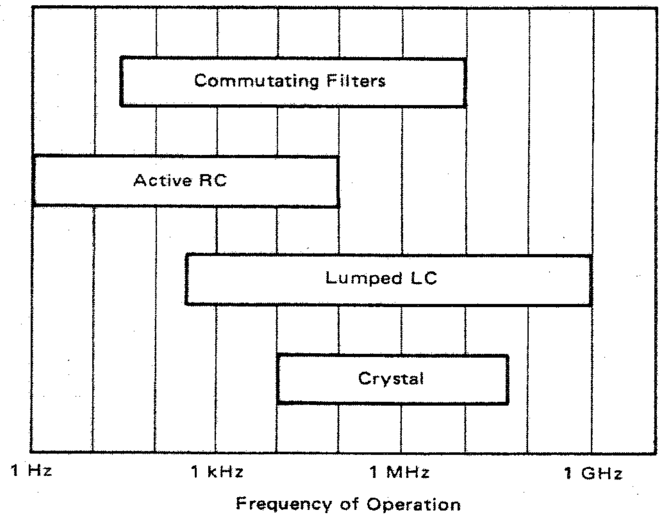
FIGURE 5 – "Comb" Filter Response

thereby generating a bandpass response with the same shape as the commutated low-pass filter defined above. Similarly, responses are generated at harmonics of f_c producing the "comb" filter response shown in Figure 5. The insertion loss for the various harmonics increases due to the relative reduction of sections and the capacitor averaging.

The "comb" filter response is not desired for most applications and a filter designed with more conventional techniques is generally used after the commutating filter. This same BPF or LPF also eliminates the step format of the commutating filter output. A low Q bandpass filter is sufficient for these purposes and is easily constructed with a minimum of practical limitations even at low frequencies.

The advisability of replacing a wave filter with a commutating filter may appear questionable since a wave filter is required in either event. Further, the range of frequencies covered by the commutating filter is common to at least one other technique as shown in Table I. Part of the usefulness of the commutating filter approach lies in reducing the required wave filter from a high Q, multi-pole device that may be impossible to realize in practice to a low Q, insensitive, and easily realizable device. Also, the other techniques have center frequencies dependent on component values and frequently do not have the stability of the commutating technique. The commutating filter can also track a changing center frequency which cannot be done easily with any of the other techniques.

TABLE I – Primary Frequency of Filter Operation



FILTER EXAMPLES

The practicality of the commutating filter for most applications is due to the availability of digital integrated circuits to replace the mechanical commutator. A shift register or counter operating at a clock frequency of Nf_c is commonly used to drive simple transistor switches. Such a filter is satisfactory if the stop band rejection requirements are not severe. The input signal must not exceed several hundred millivolts to avoid forward biasing the transistor switches. Four- and eight-section filters of this type

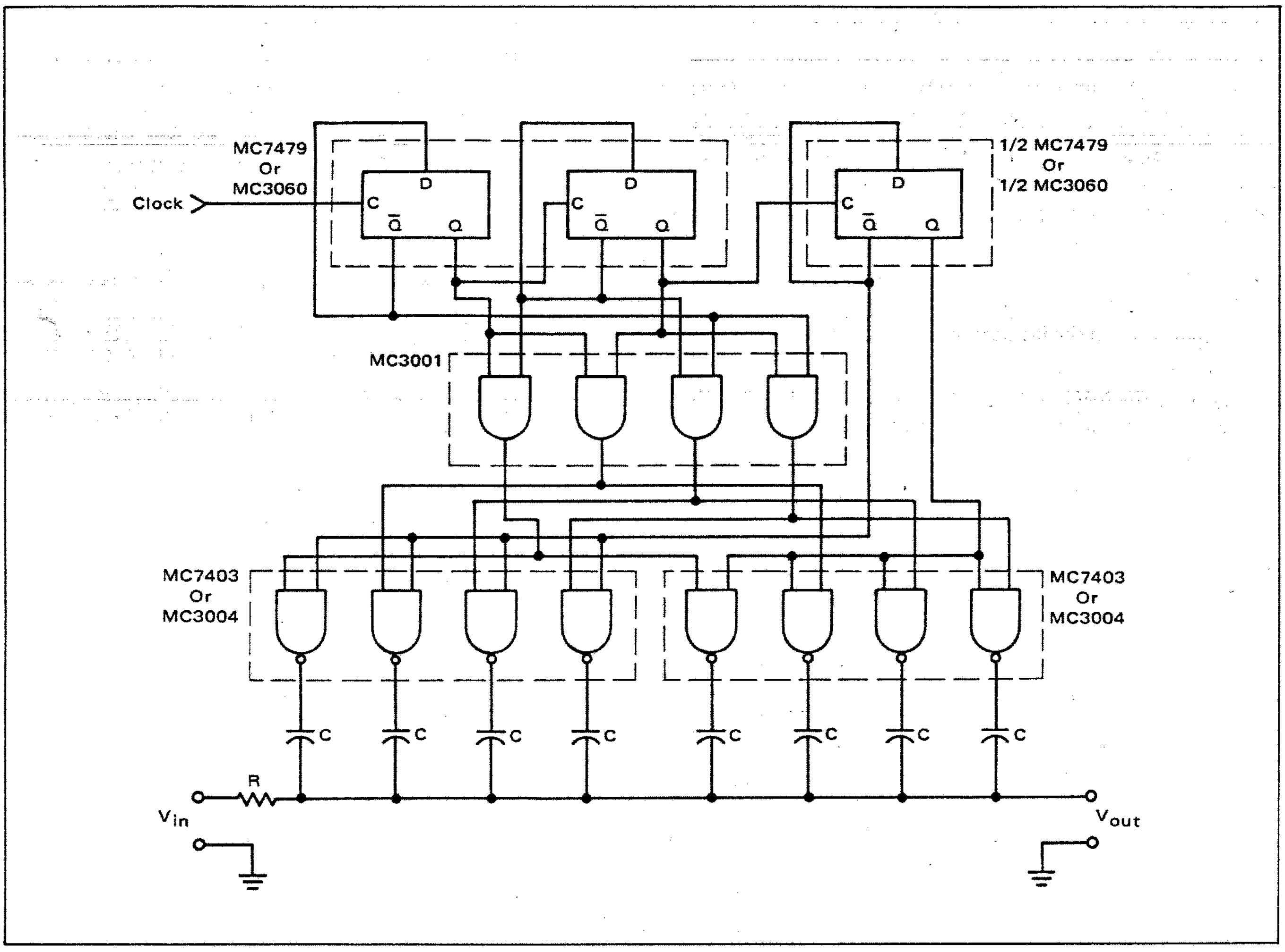


FIGURE 6a – Eight-Section Commutating Filter

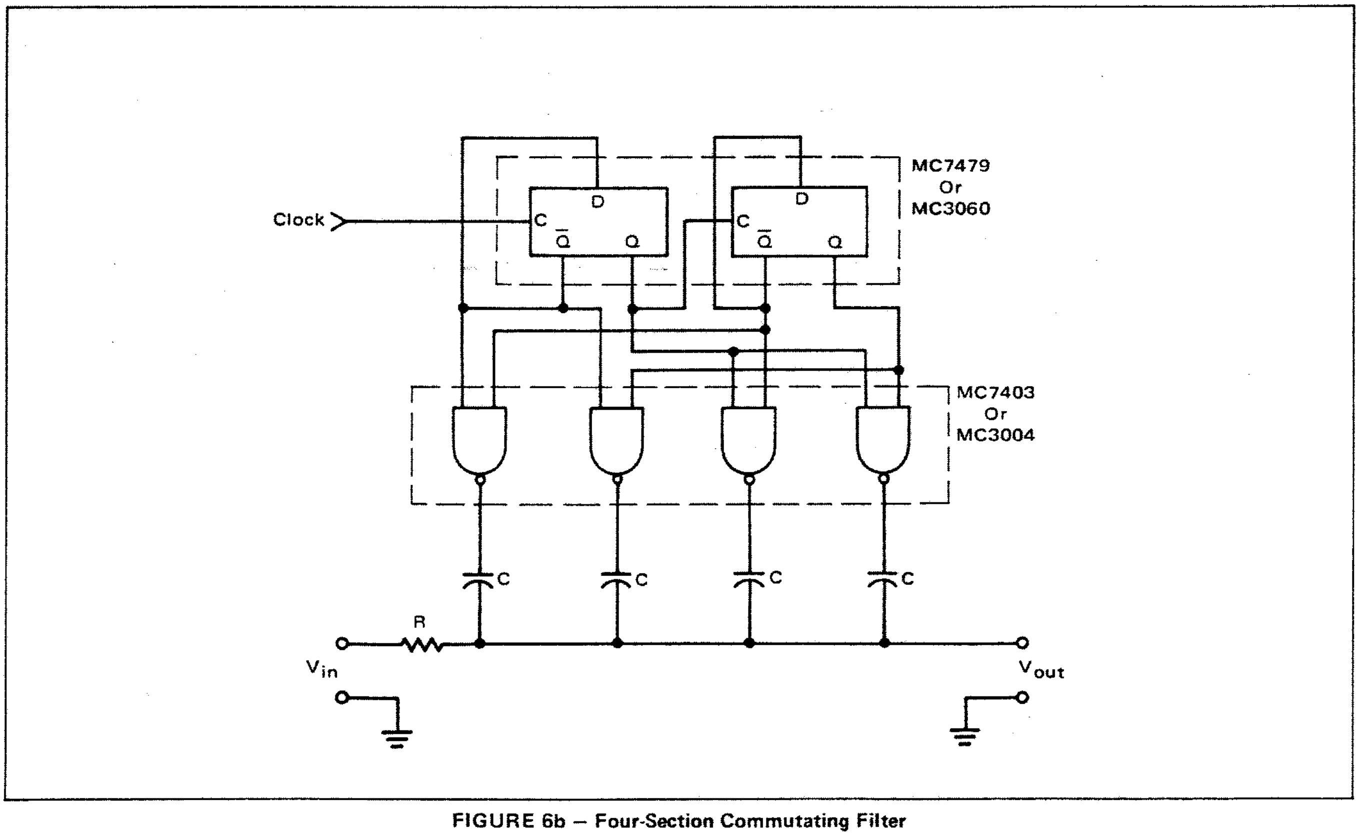


FIGURE 6b – Four-Section Commutating Filter are shown in Figure 6, with the eight-section filter having narrower bandwidth and a smoother output format. Figure 7 shows the actual response of these filters using C = 0.1 μF and R = 1 kΩ. The MC7403 open-collector gates decode the counter output and also provide the transistor switches (see Figure 6). The only discrete components required are eight capacitors and one resistor.

There is a spurious signal generated by the filter at harmonics of f_C which is a function of the saturation match of the switch transistors. This match may be increased by using transistors in the inverted mode (i.e. by interchanging emitter and collector). The resultant decrease in saturation voltage also decreases the differences between the switch transistors. Operation in the inverted mode requires discrete transistors and therefore represents a sizable increase in circuit cost to provide a small decrease in spurious signal

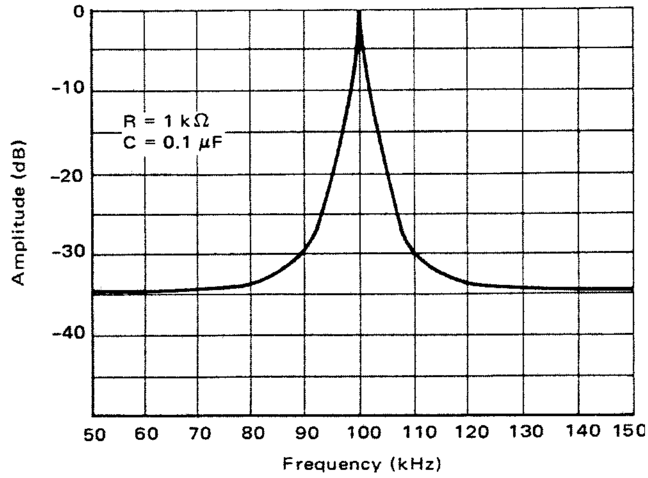


FIGURE 7 — Filter Response

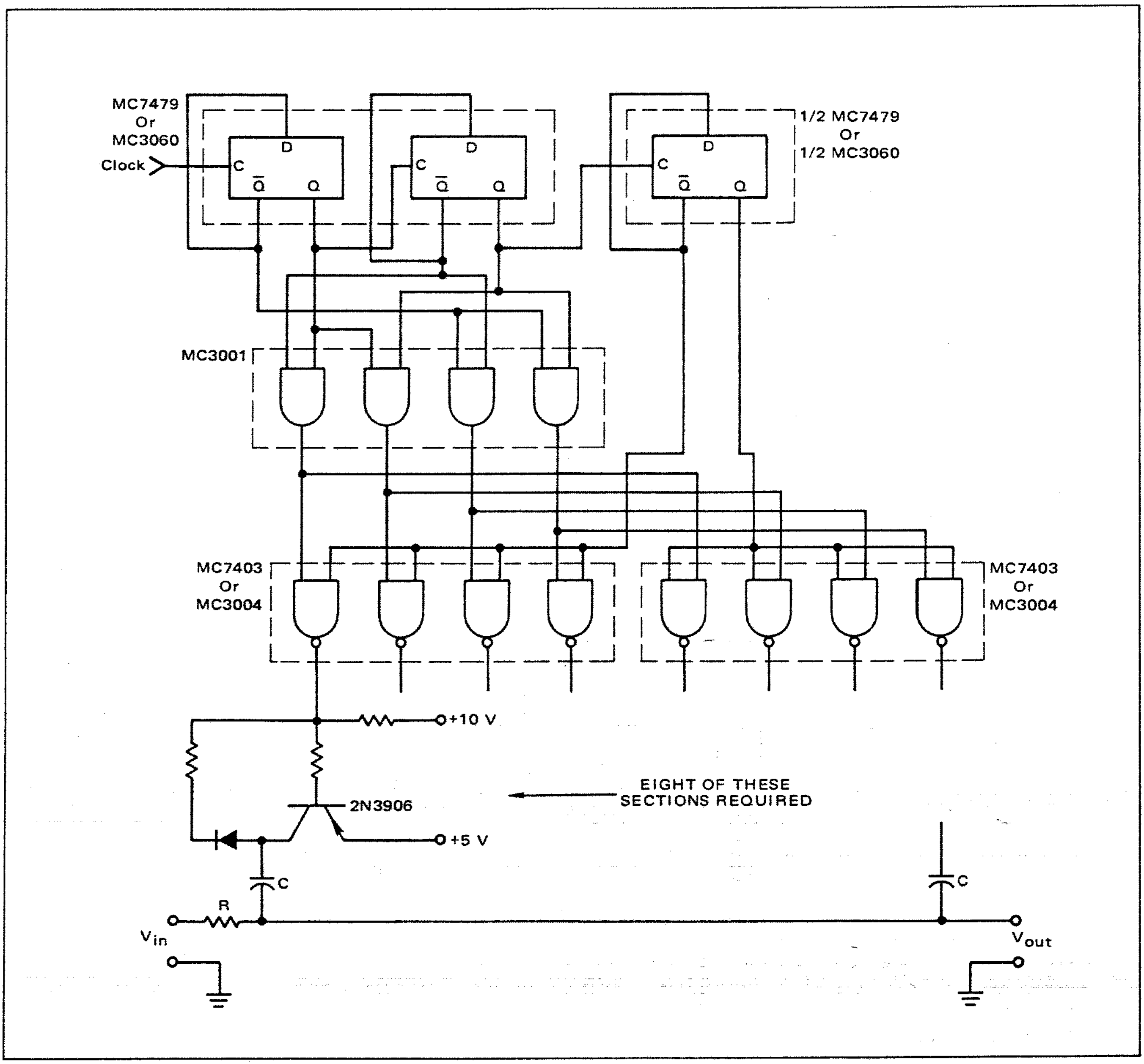


FIGURE 8 — Eight-Section Filter With Improved Switch

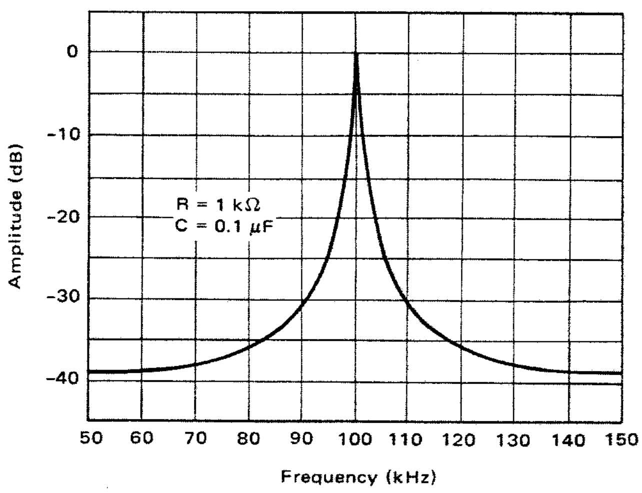


FIGURE 9 — Response of Improved Switch Filter

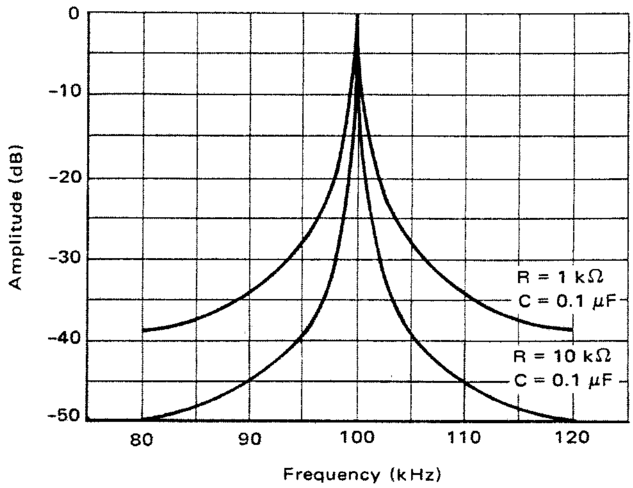


FIGURE 10 — Response of MECL II Commutative Filter

generation. If better performance is required than available with the simple switch approach, discrete components become mandatory. A switch that allows large input signals while maintaining the same saturation voltage mismatch is one option with obvious performance advantages and requires little more than one external transistor per section. The spurious signal is not decreased, but it is decreased relative to the desired signal.

The most obvious departure from theory shown by the filter is the lack of stop-band rejection as evidenced in Figure 7. This is primarily a result of a portion of the signal current being shunted through the transistor switches. This current varies the saturation voltage of the switches and is thereby transmitted through the filter. The effect of this current can be reduced by biasing with a dc current through the switch that is larger than the signal current. A network that allows larger signals and supplies dc current through the switch has been added to the filter of Figure 6a to provide the filter shown in Figure 8. These networks allow peak-to-peak input signals of 5 volts and maintain a dc current through the switch transistors for the duration of the on time. The resistor values for the network should be determined such that the dc current is greater than the largest possible current through the input resistor of the filter. The switch transistors of the networks must have a BV_{EBO} of at least 5 volts. Figure 9 gives the measured response of this modified filter. The bandwidth is the same as without the more complex switch networks, but the out-of-band rejection is greatly improved. The amplitude of the previously mentioned spuriously generated signal at f_c is 33.8 dBm.

Figure 10 shows the response of a similar filter (using MECL II logic) for several bandwidth options. The narrower bandwidth option has a higher input resistance which decreases the magnitude of signal current. The difference in stopband rejection shows clearly the advantage of reducing signal current as much as possible. A practical limit on input impedance is defined by the type of wave filter that loads the commutating filter.

The high switching speeds of MTTL and MECL are required when operating at the higher frequency limits of commutating filters shown in Table I. The stop band rejection is to a large degree proportional to the percentage of switch interval required for turn on and turn off. The MTTL turn on and off times of 10 ns in an eight-section filter dictate a maximum center frequency of about 1 MHz. The upper limit of 10 MHz can be reached only with faster (and synchronous) switching circuitry.

SUMMARY

The commutating filter can be very useful in a variety of systems as long as the departures from theory are kept in mind. Techniques have been presented for decreasing the effect of these departures and one or more of these techniques may be necessary depending on the rigorousness of the filter requirements.

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