Universal Motor Noise

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TR-83/1
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February 1983

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Universal motors are small series-wound motors which can operate on AC or DC voltage. Their light weight makes them ideal for small appliances, especially hand-held ones. Appliances which use this type of motor include vacuum cleaners, mixers, blenders, sewing machines, and portable hand-held sanders, drills, and saws. Like DC motors, universal motors contain brushes, and their performance is similar to that of DC series motors: when a load is placed on the motor, the speed decreases and when the voltage to the motor is increased, the speed increases. A series connected variable resistor can be used to obtain a continuously variable speed from the motor, and changing the field winding can be used to obtain different discrete speeds. Some appliances now use solid state switching devices to control their speed. Typical maximum speeds under load range from 3,500 rpm to 10,000 rpm. (1,2)

The current into a typical small appliance (blender) universal motor is shown in Figure 1. This figure was obtained by connecting a Fluke current probe around one wire of the appliance cord and looking at its output in real time. The current is in phase with the 60 Hz voltage driving the motor shown in Figure 2. Looking at Figure 1, it can be seen that the output current is composed of a 60 Hz fundamental frequency component, harmonics of 60 Hz which give the waveform its triangular shape, and high-frequency components which give the waveform its rough appearance. The high frequencies are attenuated somewhat by the Fluke current probe so that the high-frequency components are actually slightly larger than shown in the figure.
Figure 1. Current Into a Universal Motor

Figure 2. Voltage Across a Universal Motor
The high-frequency components were best observed by connecting a Tektronix current probe around one of the appliance cords and connecting the output of the probe through a high-pass filter to the Nicolet FFT Spectrum Analyzer as diagramed in Figure 3. The resulting spectrum from 0 to 100 kHz for one hundred averaged spectra is shown in Figure 4. Figure 5 shows the current spectrum with the device operating at the lowest speed. The speed change in this particular motor is effected by changing the field winding. In both figures the top line is the 0 dBE reference line where $E$ has been set to equal Amperes, so the top line represents 0 dBA or one Ampere. The scale is 10 dB per vertical division and 10 kHz per horizontal division. All voltage values are RMS values and a Hanning Squared window was used on the data so that the "per Hz" values are 21 dB below these RMS values for power spectral density conversion. Refer to reference (1) or the Nicolet operating manual for a complete description of the annotations in these figures.

In Figure 4 one can observe a gradually decreasing spectrum for increasing frequency out to 100 kHz, and there are also distinct peaks occurring at 6 kHz and its harmonics. In Figure 5 one can observe a slightly lower spectrum in general, and the peaks have shifted to a lower frequency. (The first peak at 4 kHz is actually higher in amplitude.) Loading the motor and lowering the 60 Hz AC voltage slightly, both of which lower the operating speed of the motor, also causes each peak to shift to a lower frequency indicating that their position is related to motor speed. Considering the operation of the
Figure 1. Current Spectrum Measurement Set-up
Figure 4. Current Spectrum of the Universal Motor for 0 to 100 kHz

Figure 5. Current Spectrum of the Universal Motor for 0 to 100 kHz Operating at Low Speed
motor, the position of the first peak should be the same as the frequency of brush opening and closing with the rotor contacts.

The high-frequency current output is practically independent of load resistance that the motor "sees". This is demonstrated by driving the universal motor as shown in Figure 6. The motor is connected to a ferro-resonant isolation transformer which supplies 60 Hz power to the motor but presents a high impedance at kilohertz frequencies. Resistances (such as incandescent lamps or other high voltage resistive loads) can be connected in parallel to provide real impedances into which the motor will operate. The results are that for resistances of 144 ohms to 13.7 ohms the high frequency current is the same.

On the other hand if the voltage is measured for different values of load resistance per Figure 6, it is found to be proportional to the resistance and the current. For computing the voltage spectrum, consider the equation

\[ V = I \cdot R. \]

Taking 20*\log\text{ of both sides gives}

\[ \text{Voltage(dBV)} = \text{Current(dBA)} + \text{Resistance(dBOHM)}. \]

The result is that the voltage spectrum should be the current spectrum increased by the resistance seen by the motor, all in dB units. This is shown in the four curves of Figure 7. Curve (a) is the high-frequency voltage spectrum for the universal motor operating into 144 ohms. It is 20*\log(144)=43 dB above the current curve of Figure 4. Similarly the curves (b), (c), and (d) are approximately 34, 29, and 23
Figure 6. Current and Voltage Spectrum Measurement Set-up
8 dB above the curve of Figure 4 for resistances of 48, 29, and 13.7 ohms respectively.

Operating into an actual wall circuit whose impedance is known produced the voltage spectrum of Figure 8. This voltage spectrum (in dBV) can be calculated by adding the current in (dRA) to the magnitude of the impedance of the wall circuit (in dBOHM). For example, using the current spectrum from Figure 4 and the wall circuit impedance obtained earlier from impedance measurements, the voltage is calculated for four frequencies as follows:

-44 dBA + 17 dBOHM = -27 dBV @ 12 kHz
-69 dBA + 21.8 dBOHM = -47.2 dBV @ 20 kHz
-77 dBA + 30.7 dBOHM = -46.3 dBV @ 50 kHz
-88 dBA + 42.7 dBOHM = -45.3 dBV @ 100 kHz

These calculated voltages agree with the voltage spectrum in Figure 8.

The voltage spectra observed at the residences agree with the spectra calculated using the current spectrum and the measured impedances except for the spectra observed at one house for frequencies of 20 kHz and below. In those spectra the voltage levels were up to 7 dB too low.

Figure 9 is an average of thirty-two 0 to 10 kHz current spectra of the universal motor. The structure of the first peak of Figure 4 can be seen in Figure 9 to be composed of several spectral lines located at 6 kHz and spaced 120 Hz apart. There are also other spectral lines located throughout that portion of the spectrum.
Figure 7. Voltage Spectra for the Universal Motor Operating Into Various Resistive Loads

a - 144 ohms  
b - 48 ohms  
c - 29 ohms  
d - 13.7 ohms

Figure 8. Voltage Spectrum for the Universal Motor Operating Into the Wall Circuit
Figure 10 shows a portion of one spectrum of width 1280 Hz and centered at 12.48 kHz. The four spectral lines spaced 120 Hz apart in the left half of the figure are part of those which form the second peak of Figure 4. Although these particular lines are 120 Hz apart, they are not located at harmonics of 60 Hz. In this expansion mode averaging the spectra will cause the peaks to round off or blur. This is because the lines are moving instantaneously because the speed of the motor is changing instantaneously (even when the motor is not loaded). The sampling time for one set of input points is 0.32 seconds. If ten spectra are averaged, Figure 11 results. From this figure it can be seen that there are spectral lines which indicate that there is noise which is periodic over the time period of the ten sample blocks (3.2 seconds) and also impulsive noise which is not periodic over that time period which gives rise to a flat spectrum.

Solid state devices such as SCR's are sometimes used in series with universal motors to control their speeds. An example of this is a portable electric drill. Figure 12 is a plot of current vs. time for the drill at high speed, and Figure 13 is a plot of current vs. time for the drill at medium speed. The DC level in this plot is zero because the probe is an AC instrument. An even lower speed reduces the time the device is on to less than half of a cycle. Figure 14 shows the high-frequency current generated by the motor for high and medium speeds.
Figure 9. Current Spectrum for the Universal Motor
for 0 to 10 kHz

Figure 10. Current Spectrum for the Universal Motor
from 11841 to 13120 Hz
Figure 11. Ten Averaged Current Spectra for the Universal Motor from 11841 to 13120 Hz
Figure 12. Current Into a Universal Motor Operating at High Speed

Figure 13. Current Into a Universal Motor Operating at Medium Speed
Figure 14. Current Spectrum for an SCR-Controlled Universal Motor at Two Speeds
In order to present a survey of the noise produced by universal motors, Figures 15 and 16 show the current spectra produced by six different appliances. Figures 17 and 18 show the voltage measured with the same six appliances operating into the wall circuit discussed previously as well as the background noise on that particular circuit.

To summarize, universal motors produce impulsive high-frequency currents whose spectrum consists of a relatively smooth spectrum and instantaneously moving spectral lines proportional to motor speed. The voltage seen across the output depends upon the product of the current and impedance.
Figure 15. Current Spectra for Three Appliances

Figure 16. Current Spectra for Three Appliances
Figure 17. Voltage Spectra for Three Appliances Operating Into the Wall Circuit

Figure 18. Voltage Spectra for Three Appliances Operating Into the Wall Circuit
LIST OF REFERENCES

