Three-Dimensional Animations of Power-Electronics Circuits Visualize Voltage and Current

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I. INTRODUCTION

A solid understanding of the behavior and interactions of circuit components is essential for work in power electronics. To become truly proficient in power electronics design, one must gain an understanding such that the behavior of current and voltage in inductors and capacitors becomes obvious and intuitive—just as the trajectory of a projectile is intuitive to a basketball player. The laws governing capacitors and inductors are as simple as those governing basketballs, so in principle gaining intuition for them should be easy, but in practice it is not.

One reason that circuits are harder to understand than basketballs is that one can learn about basketballs by watching them, whereas voltage and current are not directly visible, and must be measured indirectly with meters and oscilloscopes. This lack of visibility impedes learning about circuits in many ways, not only in lab work, but also in communication about circuits in the classroom and in paper or electronic documents. In addition, without a way to mentally visualize circuits, it can be more difficult to gain an intuitive understanding of circuit operation.

With modern computer hardware and software tools, animations can be readily produced, and have been used to demonstrate power electronic circuit behavior [1], [2], [3], [4], [5]. A new circuit animation system, initially developed for other types of circuits [6], offers potentially important advantages in showing the interactions of components, voltages, and currents in power-electronics circuits. In this paper, we introduce this system and the ideas behind it to the power electronics community, we apply it to develop animations of rectifiers and dc-to-dc converters, and we report experience using them in a power electronics course. Both the animations we have produced, and the tools used to produce new animations, will be made freely available via the Web.

In order to best facilitate gaining an intuitive understanding of circuit operation, it is important to integrate representation of current and voltage into the circuit diagram [7], rather than using physically separated animated indicators and graphs. Given this objective, it is still not immediately clear how to best visualize current and voltage. However, among those who have considered it, there is consistent enthusiasm for

representing voltage using a three-dimensional (3D) circuit diagram [6], [7], [8], [9], [10]. The first two dimensions are used for the layout of the circuit, as in a standard schematic, but the third dimension is used to represent voltage, with the vertical position of a wire corresponding to its potential. As discussed in Section II-A, we found that this visualization method, as shown in Fig. 3, best met our objectives.

There is less of a consensus on good representations for current. As discussed in Section II-B, we chose to use arrows with the length of the arrow corresponding to current magnitude (Fig. 4), as in the 3D illustrations in [11].
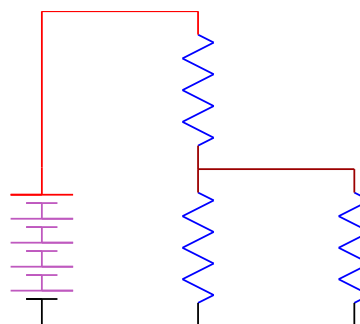

Fig. 1. A dc circuit. If you are viewing this in color, the shading of the nodes represents voltage on a scale from black, corresponding to zero volts, to red, representing 10 V.
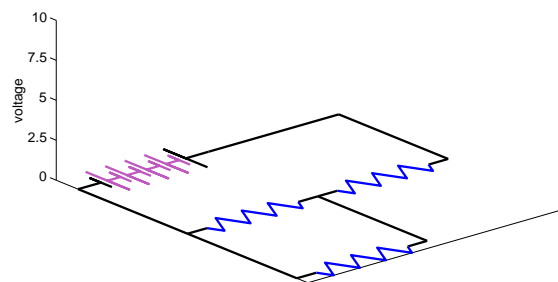

Fig. 2. The same circuit as in Fig. 1, in a 3D perspective view, with the third dimension unused.
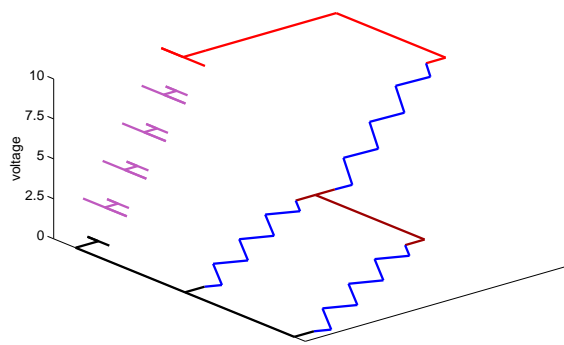
Fig. 3.   The same circuit as in Fig. 2, with the third dimension used to represent voltage.

II. Visualization Format

A. *Use of three dimensions for visualization of voltage*

An experienced electrical engineer can look at a circuit diagram and immediately see that the voltage differences across two parallel elements are the same, whereas a beginning student may need to define variables, write an explicit Kirchoffs voltage law (KVL) equation, and often then correct the sign errors made in these steps in order to arrive at the same conclusion. Helping students gain intuition for KVL is important to helping them get to a higher level of proficiency more quickly. We would like for them to be able to literally see how voltage drops across different elements are related. Understanding Kirchoffs current law (KCL) is also important, although it seems easier for students to grasp this intuitively, based on the idea of conservation of charge. Thus, illustrating KCL is also an important objective, but a good representation of voltage takes priority. As discussed in more detail by [7] and the references cited therein, it is valuable to make the display of variables integral to the representation of the system—meaning, in this case, on the circuit diagram, and, to the extent possible, integrated with the symbols representing components and connections on the diagram. An adjacent graph or other indicator can be useful, but the process of

Fig. 4.   The same circuit as in Fig. 3, with arrows added to represent current.

matching legends, colors, or other indications is distracting, and is always one step removed from the circuit. Our goal is to enable students to see what is happening by watching the circuit without any extraneous mental steps.

Possible ways to represent voltages on a circuit diagram include indicators such as bar graphs, meter analogs, or even text numbers next to components or [12], [13]; shading nodes in different colors corresponding to voltage, as in Fig. 1, or using the third dimension for voltage, as in Fig. 3. Three-dimensional diagrams have clear advantages. They make KVL immediately apparent, and in fact make the very idea of violating it as counter-intuitive as an M.C. Escher drawing [6]; they allow semi-quantitative estimations of relative and absolute voltage drops [7]; and they provide an intuitive analogy between gravitational potential energy and electrical potential energy, although, as noted in [7], one must be careful to explain the limitations of this analogy.

Thus, we choose to use the 3D representation of voltage. We also shade nodes according to voltage. This is intended to communicate the same voltage information over more channels, and to reinforce the suggestion that students in introductory electrical engineering classes color nodes themselves as they analyze circuits. For resistors and inductors, the voltage is shown dropping linearly over the length of the active element. However, for capacitors, the potential of the plate should be the same as the potential of the wire it is connected to, and this is how we depict it (see, for example, Fig. 8). This follows [9], but differs from the representation used in [7], where a section of the diagram including the capacitor and its leads is ramped the same as resistors.

We use a new way to represent voltage on a diode that is a hybrid between the two styles, as shown in Figs. 5-7. When the diode is off, the two ends of the diode separate, and the potentials each follow their respective nodes. However, when the diode is conducting, the body of the diode is shown slanted, indicating a voltage drop across the junction, without the disconnection effect shown in the reverse-bias case. The "on" or "off" state of the diode can be controlled independently of the voltage polarity to demonstrate reverse-recovery effects.

B. *Visualization of current*

Although we have four precedents for the use of the third dimension to represent voltage [7], [9], [10], [11], they all use different representations of current, or omit current from the visualization on the schematic [9]. Because current is motion of charge, moving objects can represent that motion, for example with small spheres of charge moving along a circuit path [10] or with dots moving along wires in a schematic [1], [2], [3], [12]. In [7], current is represented by a vertical ribbon underneath of the current path, with the vertical width of the ribbon representing current magnitude, and arrows on the top indicating current direction. We chose to simply use an arrow adjacent to a component or branch with the length of
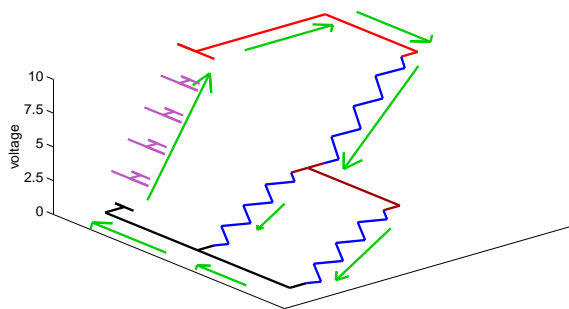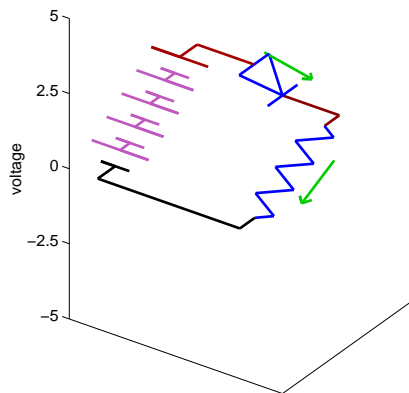
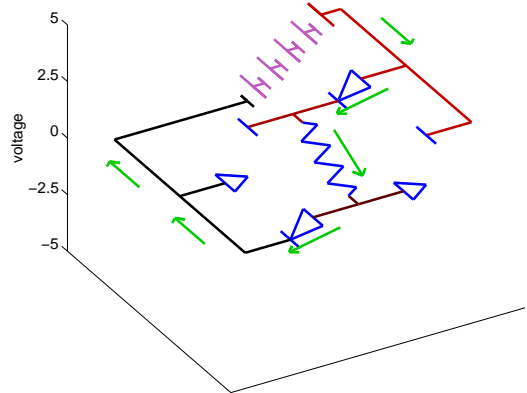Fig. 5. Snapshot from an animation of a simple half-wave diode rectifier.

Fig. 6. Snapshot from an animation of a bridge rectifier. In this animation, one end of the ac input voltage is grounded; i.e., it is used as the zero-volt reference for the vertical axis. In a variation of this animation, one side of the resistive load is grounded.

the arrow representing magnitude, as in Fig. 4 [6], [11]. Each of the various current representations have advantages [6]; we chose arrows because the intuitively integrate representation of current direction and magnitude, and allow rough semi-quantitative assessment of relative magnitudes.

The representations of voltage and current should be as different as possible, since these are fundamentally different quantities. The combination we use works well for this: the direction in which the current arrow grows and shrinks is generally orthogonal to the vertical direction of voltage. At the same time, however, the arrows tilt to follow the potential difference between two nodes. This means that current arrows for resistors always point downhill, and that current arrows for inductors always grow in the downhill direction or shrink in the uphill direction. This builds intuition both by showing a consistent correlation, and by drawing on the gravitational analogy.

III. Implementation

Animation of the visualization schemes described in Section II and shown in Figs. 4-10 has been implemented in a set of MATLAB [14] functions [6], which may be downloaded freely on the Web [15].

To create an animation of a new circuit with our tools, one must write a new MATLAB script or function that consists mostly of calls to functions that are part of the "toolbox" we provide. An example is included in the Appendix. A data structure representing the circuit, including graphical objects and other information, is built up by a series of function calls, each of which adds a component or wire to the circuit. The circuit is constrained to a grid of regularly spaced nodes. To add a component, one need only specify the numbers of the two nodes it is connected between, and the component type. This is similar to, but simpler than, the process of defining a circuit in a SPICE netlist. Similar function calls are used to add current arrows where they are desired.

After defining the circuit and current arrows, one must also manually specify the dynamics of the circuit; no automatic calculation of dynamics is included in the present version of the software. Often, one already knows simple equations for the behavior of a circuit one is presenting to a class, so a user who is familiar with MATLAB syntax can easily write a few lines of MATLAB code to calculate the circuit dynamics. What is needed is a matrix with the voltage at each of the nine nodes at the time corresponding to each frame in the animation, and a second matrix with the currents for each current arrow used. If switches, diodes, or other components that can visually change state are used, a matrix of their states must also be defined. The data for the circuit dynamics could also be generated by a simulation using MATLAB tools for solving differential equations, or by importing data from external circuit simulations.

After a call to an initialization routine, a call to an animation function produces an animation. Periodic functions can be implemented by putting this animation function call in a loop. The animation can be paused to wait for a keystroke at predetermined points, or the animation can be manually paused. The viewing angle of the three-dimensional scene can be set within the code defining the circuit, or can be manually changed with a mouse while the animation is running.

In order to make it possible for students to easily view animations without installing MATLAB and the animation functions on their own computers, some animations have been converted to Graphical Interchange Format (GIF) using an inexpensive commercial tool [16]. This results in compact files compatible with Web browsers. For the line art in these animations, GIF was found to be superior to video-oriented compression schemes, giving smaller file sizes and better quality.
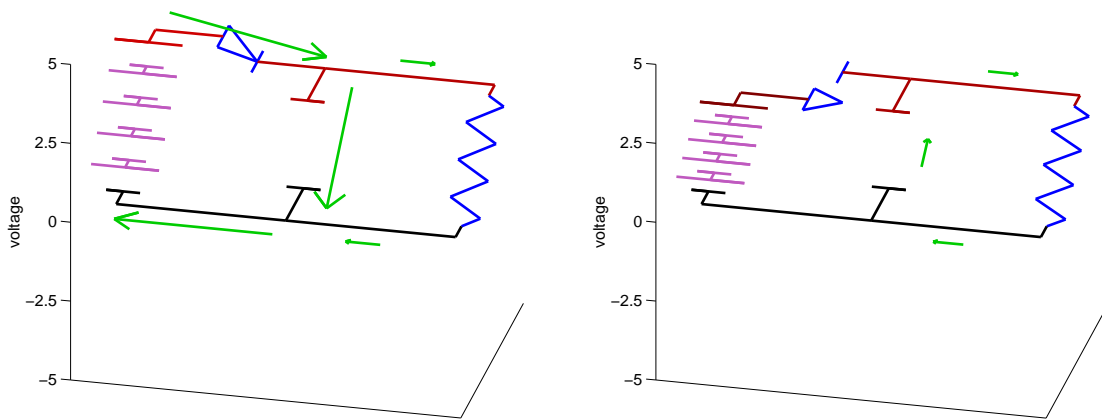
Fig. 7. Two snapshots from an animation of a half-wave rectifier with a capacitive filter. When the diode is on, the voltage drop is shown occurring across the arrow portion of the diode. When the diode is off, it is shown disconnected. The logical state can be controlled independent of the voltage polarity, in order to illustrate reverse-recovery.
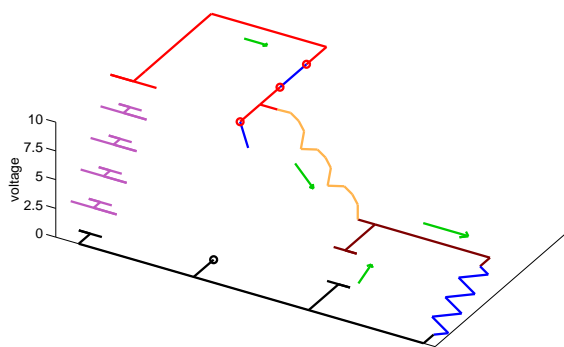

Fig. 8. Snapshot from an animation of a buck converter. Parameters chosen to be easily adjustable are the ripple ratio (inductor value), conversion ratio (duty cycle) and output capacitor value. A discontinuous-mode animation has also been produced.

Fig. 9. First snapshot from an animation of a boost converter.
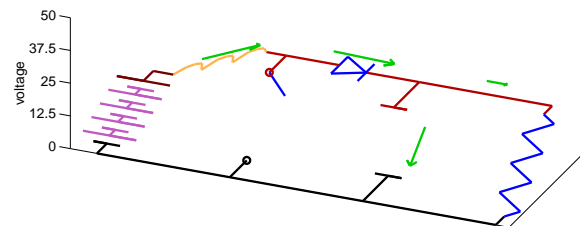
Fig. 10. Second snapshot from an animation of a boost converter.

IV. Power Electronics Examples and Experience

Power electronics circuit animations that have been implemented include rectifier circuits and dc-dc converters. MATLAB users can download the functions implementing these, and run them "live." Running the animations "live" in MATLAB has the advantage that the user can easily specify parameters such as conversion ratio and ripple ratios, and can change the viewing angle as the animations runs.

Unfortunately, in this paper, we can only provide snapshots of some animations. These are shown Figs. 5 to 10; see the figure captions for details and descriptions of other animations that have been developed. The animations corresponding to these snapshots and more can be viewed on the Web site [15]

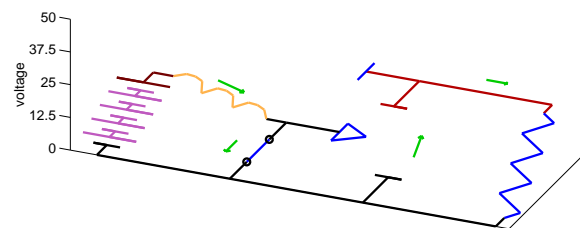Animations as described above have been used in the classroom and lab for three courses: a sophomore-level interdisciplinary lumped-element systems core course and an introductory analog electronics course, as well as a power electronics course. They were enthusiastically received in all the courses. Students surveyed in the systems course rated its "effectiveness at helping [them] learn," the highest of fifteen aspects of the course addressed in the survey, and made comments such as "Really helped me understand what was going on. Key!"

V. Conclusion

3D circuit animations can be highly effective in helping students learn. Because understanding the interactions of

components, voltages, and currents is essential for power electronics, these animations are particularly useful in this field. New software simplifies the process of producing animations [6]. In this paper, we introduce animations of rectifier and dc-to-dc converter circuits. Students react positively to the use of these animations in power electronics courses.

APPENDIX
SAMPLE CIRCUIT FILE

```
%Circuit animation of capacitor connected to 120 V rms line.

%%%%%%%%Set up and clear figure%%%%%%%%%%
aninit

makegrid(3,3)     %sets of a 3 x 3 grid of circuit nodes.
% Components may be placed between any of the numbered nodes
% Wires must also be placed
% between numbered nodes to complete the circuit.
% To view the numbering of nodes for any size,
% use the function showgrid(n,m).  The grid we are
% using (obtained from showgrid(3,3) is
% 7 8 9
% 4 5 6
% 1 2 3

%%%%%%%%Add components to circuit cell struture "ca"
ca = addV(ca,1,4);
ca = addwire(ca,4,5);
ca = addwire(ca,1,2);
ca=addC(ca,5,2);

%%Add current arrows to current cell array "ia"
ia = currentarrow(ia,4,5,1,0);
% Capacitor current, shown in "top" wire to cap.
% Numbered current 1
ia = currentarrow(ia,2,1,1,0);
%Cap current, shown in "bottom" wire to cap.
%Numbered current 1 again, because it is the same.

%%%%%%%%%%%Calculate voltage as a function of time
nframes=200;

% Column vector of times of frames:
t = linspace(0,1/60,nframes)';
%calculate voltage vector for each frame:
vin = 170*sin(2*pi*60*t);
z = zeros(nframes,1); % column vector of
%zeros to use for zero-voltage or unused nodes

% Voltage matrix--each row is a time snapshot
% of voltage at each node. Each column is a
%time history of the corresponding node.
vm = [z z z vin vin z z z z];

%%%%%%%%%%%Calculate current
icap=cos(2*pi*60*t);
%Current is derivative of voltage, scaled to max of one.
im = [icap];
% im is the current matrix; same format as
% voltage matrix, but with columns only for
%currents the user has numbered (in this case just one.)

rate = 20; %nominal frames per second.

%%%%%%%%%SET UP
vm_scaled=aniset(vm);  %Set up scaling on the graph, etc.
cvm=vm_scaled;  %A separate matrix, cvm, is used to specify
% the voltages used to set color of wires; this allows different
%scaling of the color and vertical axis if desired.

view([ 35, 30]);  % azimuth and elevation

%%%%%%%%%%%%%RUN
canimate(t,vm_scaled,cvm,im,ca,ia,rate,cvm);
```

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