An efficient pedagogical approach for integrating power electronics, drives and the PMDC motor into the traditional energy conversion course

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Abstract

Over the last 40 years, the advent of power electronics has extensively impacted almost every aspect of Electromechanical Energy Conversion (EMEC). The effective integration of power electronics, electric drives, and system related issues into the EMEC curriculum demanded a significant redesign of both the course and laboratory exercises. Using a "just-in-time" strategy, four laboratory exercises and corresponding lecture material associated with the buck and boost switch-mode power supply (SMPS), the 2- and 4- quadrant drive, and the permanent magnet DC (PMDC) motor has been developed. Before introducing SMPS, the fundamental operation and electrical equivalent of the PMDC motor is established. Using the volt-second energy balance approach, the buck and boost SMPS and their voltage transfer characteristics are developed. Using the principles of duality, the SMPS is extended to the 2-quadrant drive for the PMDC motor. Three laboratory exercises, associated with these topics, are conducted very near the presentation of the lecture course material. These three exercises culminate into a fourth exercise involving a 2-quadrant drive used as a power-processing converter between a solar array and a submersible solar-powered pump. An efficient pedagogical approach integrating these topics has resulted in a concise set of lecture materials and exercises. Elements of the course material and exercises are presented in this paper.

I. Introduction

Today, electric machines are very frequently only one component in an EMEC *system* (frequently referred to as a “drive”). Power electronic devices have enabled unprecedented control over and flexibility of EMEC, and because of their tremendous advantages such devices have become extremely common in practice and continue to become more prevalent[1]. Greater than 20 percent of motors produced require some form of electronic motor control[2], strongly suggesting that electrical engineers should acquire a sufficient understanding of the power electronic drives in addition to the fundamentals of the electrical machine. Clearly, the "traditional" education in EMEC, which considers electric machines in isolation and barely mentions power electronics, no longer adequately prepares undergraduate students for a career in power engineering. The effective integration of power electronics, electric drives, and system related issues into the EMEC curriculum demands significant redesign of both the course and laboratory exercises. One such redesign is currently being supported under the Adaptation and Implementation track of the NSF's CCLI program at South Dakota State University[3]. Emerging from this work is an efficient pedagogical approach for integration of power electronics, drives and the permanent magnet DC motor.

Using a "just-in-time" strategy, successfully developed at University of Minnesota[4] and further modified at SDSU[3], four laboratory exercises and corresponding lecture material associated with the buck and boost switch-mode power supply, the 2- and 4- quadrant drive, and the permanent magnet DC motor has been developed. Each distinct set of materials has a corresponding laboratory exercise (made available to the public via http://learn.sdstate.edu/shietpas/asee/index.htm) that is conducted very near the time the lecture material is presented. The student is first reacquainted with Faraday and Lorentz laws before the PMDC motor electrical-equivalent model is developed. Second, the buck and boost converters and their voltage transfer characteristics are developed using the volt-second energy balance approach. Third, the 2-quadrant drive is presented as an extension of a combined buck and boost converter attached to the PMDC motor. The principle of duality is stressed as well as the similar functionality of components in the SMPS that also exist in the 2-quadrant PMDC motor drive. This approach allows for the concept of motoring (buck) and generating (boost) to be conveniently extended. Last, the 4-quadrant converter is developed using the volt-second balance approach. To assist in this development, improved drive switching schemes (beyond those used in the simple buck and boost converters) are presented. The first three laboratory exercises require the students to model the PMDC, analyze and test a buck converter, and then modify the buck converter to a 2-quadrant drive for the same PMDC. Each of these lab exercises contains a PSpice simulation component. These three exercises culminate into a fourth exercise involving a 2-quadrant drive used as a power-processing converter between a solar array and a submersible solar-powered pump. This last exercise also meets the system level objective outlined in a previous paper[3]. Preliminary results from student feedback are encouraging, indicating that the accelerated approach is feasible.

The paper is divided into six sections. Section II through V are dedicated to the essential material and exercises associated with each of the four topics, i.e., PMDC motor, the buck and boost SMPS, the 2-quadrant drive, and lastly the 2-quadrant drive, PV array, and submersible pump system. Within each section, a brief development of governing equations, a summary of the exercise and corresponding objectives and outcomes is presented. The pedagogy that efficiently aids in the transition from one topic to the next is accentuated. The paper concludes with section VI.

II. PMDC Motor

The importance of system level design is not usually addressed sufficiently in most undergraduate courses, possibly due to the fact that most courses center on a single subject area that does not lend itself easily to the consideration of a complete system. In an Electric Drives and Machines course the instructor is able to provide a systems level approach to engineering design. An EMEC system is comprised of the electric drive, motor and load. Torque vs. speed profiles for a variety of loads should be addressed as early on in the semester as possible since any application is primarily concerned with the control and movement of a load, such as a pump, fan or conveyor belt. While it is worthwhile for students to perform lab tests to obtain load profiles, it may be prudent, in the interest of time, to provide the load profile to the student at the outset of a lab exercise. Taking this approach and the desire to proceed as quickly as possible to exposing students to a rotating machine, the development of the equivalent circuit model for a PMDC motor is developed in lecture. Particular attention is given to the back emf produced by the machine and its dependence on motor speed and inertia of rotating mass in the machine. The primary reason for particular attention given to this element of the equivalent circuit model is their counterparts to the storage (filter) capacitor found in the standard buck and boost SMPS.

The equivalent PMDC circuit model is shown in Fig. 1. Students are tasked to perform a series of steady state and transient tests to obtain numerical values of the equivalent electrical circuit parameters for a permanent magnet DC motor. These parameters include armature resistance, inductance and the machine torque constant.

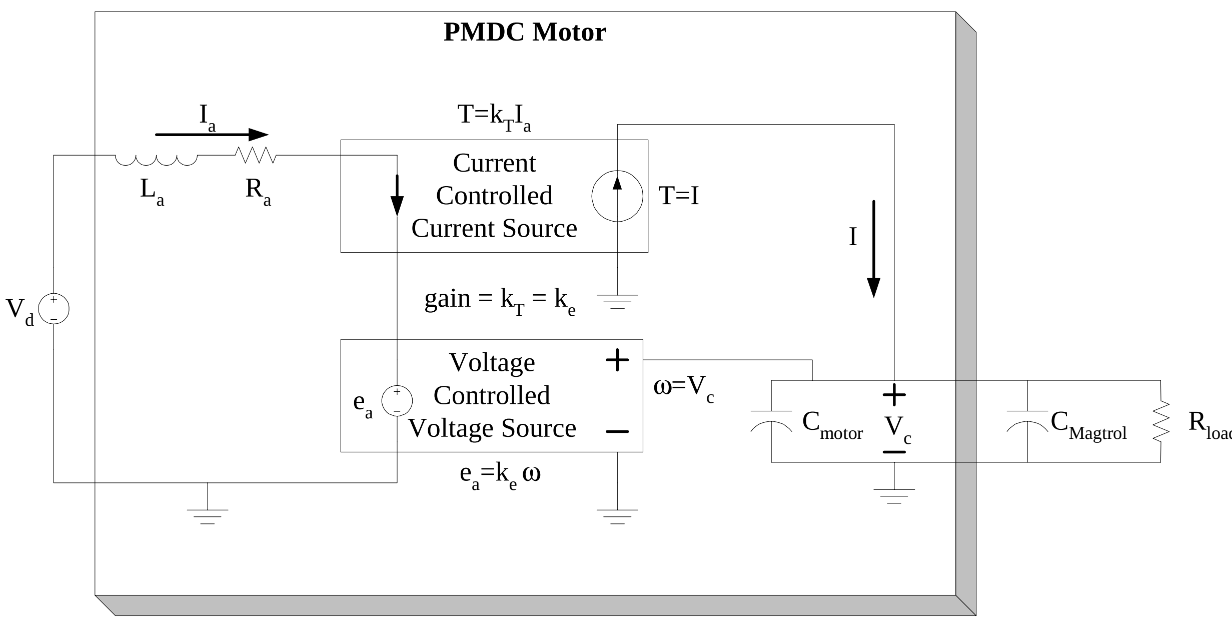


Figure 1: PMDC motor electrical equivalent PSpice circuit

While many manufacturers provide motor parameters, it is important for students to perform tests to determine their accuracy. A ½ hp motor from Dynetic Systems Incorporated (MS3130-04/T-21/S) was tested in lab using the Magtrol DSP6001 (6000) Magtrol Controller and HD-715-6N Hysteresis Brake (motor load) system. Students performed the appropriate tests and using a spreadsheet routine computed for L_a, R_a and k_T. Comparing their results to parameters provided by the manufacturer, they soon discovered that while R_a and k_T were relatively close to manufacturer parameters, L_a differed by as much as 100%. The test procedure followed by the students includes a simple startup transient test, where it is assumed that the back emf $e_a = 0$ and the step input voltage V_d is held constant for the time period of interest. Using the simple first order differential equation describing the behavior of an RL circuit, it is not difficult to obtain a reasonable value for L_a. Students are encouraged to determine why their value L_a differs so greatly from that of the manufacturer's, before the instructor reveals to them that the manufacturer test for obtaining L_a is arrived at through the use of an LCR bridge, which operates the motor with a 60 Hz source (not an appropriate method for obtaining L_a for a PMDC motor). Further confidence in the student's parameters is gained through PSpice simulation data using their parameters and then the manufacturer's parameters compared to actual laboratory data from additional tests that were exclusive of those tests used for establishing circuit model parameters.

This approach to EMEC system development is straightforward and quite revealing to students. Through these exercises, we have found that students are surprised that not only is the circuit model for the DC motor simple but that the mechanical system can so easily be simulated in PSpice! Also, students see how important it is to not always trust manufacturer data sheets and that good engineering often requires additional tests to gain confidence in the equivalent models being used. Details regarding the associated laboratory exercises can be obtained at the following locations:

http://learn.sdstate.edu/shietpas/asee/asee02/lab_5_1.pdf
http://learn.sdstate.edu/shietpas/asee/asee02/lab_5_2.pdf

A firm understanding of the PMDC and its equivalent circuit model along with a keen understanding of the correlation of motor speed, back emf and motor inertia help motivate the next sequence of lectures involving the Buck and Boost SMPS.

III. Buck and Boost SMPS

The student is often first exposed to power electronics in the EMEC course. Though the basic principles of sequential switching is first introduced in their first and second courses in circuit analysis, extending these principles to the understanding of the buck and boost SMPS can be challenging to the student.

Mohan's[1] approach to the introduction of the SMPS and Drives is elegant and efficient and is especially suited for those interested in incorporating closed-loop feedback modeling and design within the course. Mohan starts from the basic topology of a DC input source, single-pole double throw (SPDT) switch, output choke inductor, and controlling input that determines the duty cycle of the SPDT switch. The SPDT switch is further described as a voltage to current port ("transformer") dependent on the duty cycle and from a small signal approach is easily modeled in PSpice and extremely conducive to controller modeling and simulation[5]. Furthermore, this approach also lends itself well in the development of polyphase drives.

My experience in teaching electric drives within the machines course over the last two years, and as a result of the different curriculum requirements in our program compared to those at the University of Minnesota (UM), has led to a slightly different approach in the development of the SMPS. (The main difference in our curriculum is that the linear control systems course is a technical elective rather than a required course as it is at UM). Not pursuing the controls aspects does allow for increased development of the SMPS (though, if I had a choice, I would rather incorporate controls into the course).

After teaching SMPS using the "Mohan" approach the first time, I found that students were too far removed from the practical understanding of the actual implementation and operation of the SMPS. To circumvent this deficiency, I chose to develop the SMPS based on the volt-second energy balance approach. Furthermore, increased attention was given to the various strategies of generating the switching waveform and duty-cycle control signal. The development closely correlated with "Mohan's" approach, hence, not abandoning the possibilities of considering the controls aspects of electric drives. The buck SMPS is shown in Fig. 2. The switch SW_1 and the flyback diode D_f comprise the SPDT switch as described in Mohan, hence SW_1 and D_f serve as the voltage to current port. The volt-second approach teaches the students the fundamental principle of energy conservation (assuming ideal case) and helps to the establish steady state operation of the converter. Furthermore, coupled with the development of the method of generating the PWM control signal, this approach greatly aids in their understanding of the converter when working with the SMPS in the laboratory.

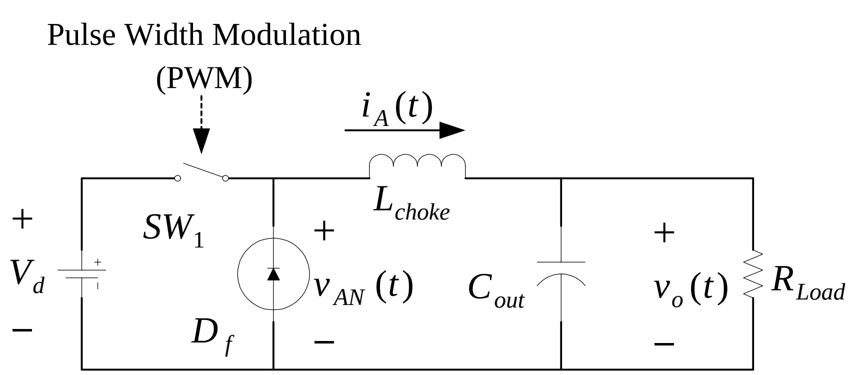


Figure 2: Buck SMPS with dc input

The volt-second approach starts with the fundamental equation $V_{L_{choke}} = L_{choke} \frac{di_A(t)}{dt}$. When SW_1 is in the down position for t_{on} seconds, energy is delivered to L_{choke} and when it is up for t_{off} seconds, energy is delivered from L_{choke} to the load. From a volt-second approach it is easily established that $(V_d - V_o)t_{on} = V_o t_{off}$. Letting d_A represent the duty cycle of SW_1, the governing transfer function equation between the input and output of the buck converter is given by $V_o = V_d \frac{t_{on}}{t_{on} + t_{off}} \equiv d_A V_d$. This approach lends itself well to further investigation into peak and average values of current, those elements that dictate the choice of power semiconductor switches and other components within the converter.

At this point in the sequence of lectures and material within Mohan's textbook[1], the PWM signal is developed further by introducing the switching triangular waveform $V_{tri}(t)$ and the control signal $V_C(t)$ that help to establish the desired PWM controlling input to the main switch. Mohan's development assumes a triangular signal biased at 0 Vdc, with $\pm\hat{V}_{tri}$ peak values. From this development, it is shown that d_A, as a function of the control voltage and peak value of the triangular waveform, is given by:

$$d_A = \frac{1}{2} + \frac{V_C}{2\hat{V}_{tri}}$$

To coordinate our course material with elements taught in other courses, we chose a SMPS design as shown in Fig. 3. Though the generation of $V_{tri}(t)$ and PWM can be realized through any number of standard PWM ICs, we chose to use principles from electronics and generate our own PWM signal using standard discrete components (i.e., comparators, resistors and capacitors). The LF411 is a comparator and the IR2117 is a differential driver suitable for this design.

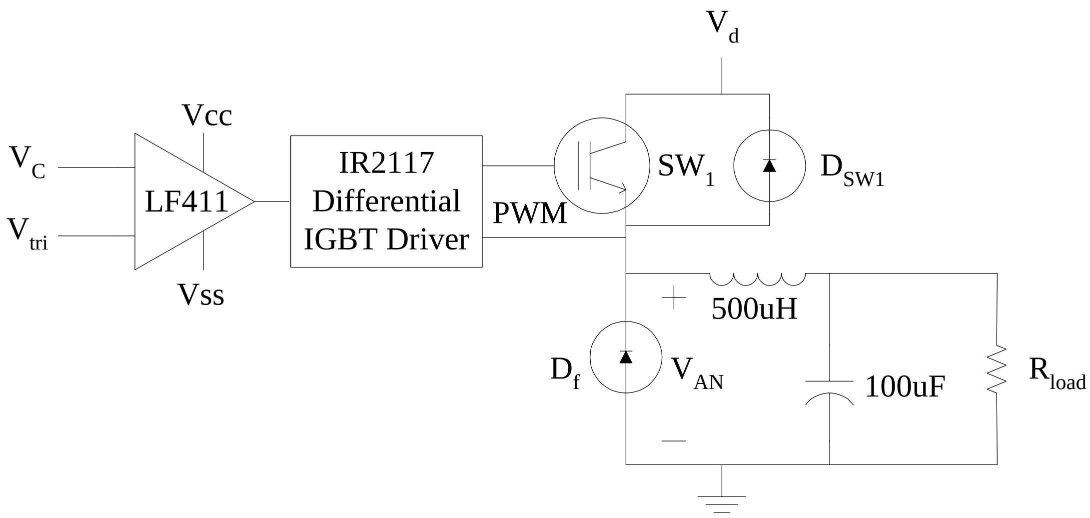
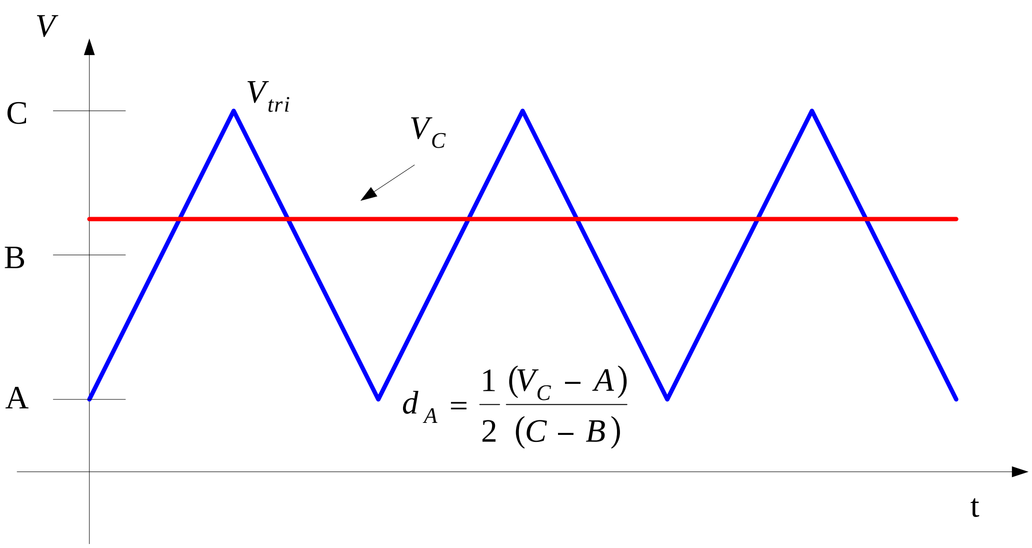


Figure 3: Buck SMPS circuit diagram.

To insure that the student completely understands the interaction of the triangular waveform, control signal, and duty cycle of the PWM signal, the student is asked to confirm the relationship for d_A given the actual triangular waveform of V_{tri}, as shown in Fig. 4. This waveform closely resembles the actual triangular waveform they experience in the laboratory.



$$d_A = \frac{1}{2}\frac{(V_C - A)}{(C - B)}$$

Figure 4: Triangular switching signal for the buck SMPS

The associated lab exercise requires the student to build a portion of the converter, obtain key values such as minimum and maximum duty cycles as defined by *A*, *B*, *C* and V_c (Fig. 4).

According to these minimum and maximum duty cycles, the student investigates the SMPS minimum and maximum output voltage capability for an input voltage of 70 to 100 Vdc, unloaded and nominally loaded. Students also must take into account non-ideal characteristics of the power switches when investigating the performance of the buck SMPS. In their post analysis, a PSpice model of the entire circuit is constructed and simulated for comparison to actual lab data.

This approach to the study of the fundamentals of SMPS provides the student with both a higher-level elegant approach to the simplicity of the converter as seen in Mohan as well as a practical understanding of energy transfer based on the volt-second approach. The volt-second approach also allows for the development of insightful laboratory experiments. Details regarding the associated laboratory exercise can be obtained at the following location:

http://learn.sdstate.edu/shietpas/asee/asee02/lab_6_1.pdf

A firm understanding of the PMDC, its equivalent circuit model, and the buck SMPS allows for an efficient expansion to the boost converter, the two-quadrant and four-quadrant motor drive.

IV. 2- and 4-Quadrant Drives

Motors can operate in 1 of 4 quadrants. Table 1 describes the relationship between input voltage, speed and current for each of the four quadrants for the PMDC. The PMDC armature voltage is v_a, armature current is i_A, counter emf is e_a, and speed is ω_m.

Table 1: 4-quadrant operating modes of a the PMDC motor

Quadrant	Description
I	Forward Rotation $\omega_m > 0$, $v_a > e_a > 0$, and $i_A > 0$, Motoring
II	Forward Rotation $\omega_m > 0$, $e_a > v_a > 0$, and $i_A < 0$, Generating
III	Reverse Rotation $\omega_m < 0$, $\lvert v_a \rvert > \lvert e_a \rvert$, $v_a < 0$, and $i_A < 0$, Motoring
IV	Reverse Rotation $\omega_m < 0$, $\lvert e_a \rvert > \lvert v_a \rvert$, $v_a < 0$, and $i_A > 0$, Generating

Quadrant pair (I,II) have their dual in quadrant pairs (III,IV). Hence, in the interest of time, we limit our discussion to quadrant pair (I,II).

Note that in quadrant I, the characteristics require a drive identical to the buck converter, where the output voltage is less than the input voltage. In the buck SMPS the output voltage is sustained by the output filter capacitor, in the dc motor case, the output voltage is sustained by the back emf, e_a.

Note that in quadrant II, the characteristics require a drive "similar" in topology to the boost converter. The back emf, e_a, now takes the place of the boost SMPS's input voltage, and the boost's output filter capacitor is now the supply voltage of the dc drive. This comparison is most easily understood through careful observation of the schematic diagram in Fig. 5. While observing this diagram, make careful note that the current flow under "boost" operation flows from larger voltage source to smaller voltage, i.e., generating mode of operation.

While motoring (quadrant I) only switches SW_I and diode D_I are operational. This topology is identical to the buck SMPS. While regenerating (quadrant II) only switches SW_{II} and diode D_{II} are operational. This topology is similar to the boost SMPS.

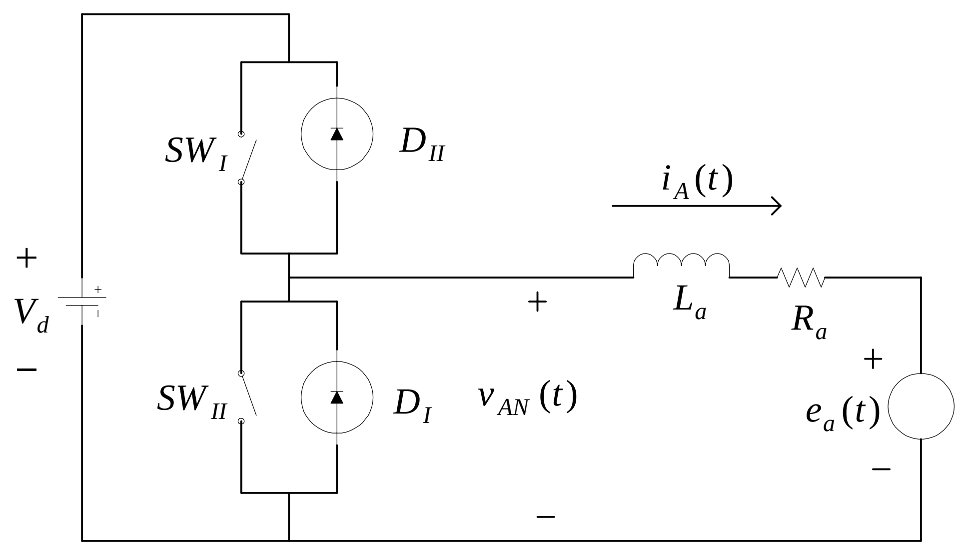


Figure 5: Two-quadrant PMDC drive

Mohan[1] developed fundamental principles of the two and four-quadrant dc drive using the voltage port to current port method. This method is straightforward and quite useful when simulating in PSpice using Analog Behavioral Models (ABMs) to generate the PWM signal, especially under closed-loop feedback control[5].

The advantage of only extending the buck SMPS to a 2-quadrant PMDC motor drive, instead of a 4-quadrant drive, is 1) to avoid overwhelming students with unnecessary complex circuitry, 2) allow students to quickly see the topologies of the buck and boost converters imbedded in the 2-quadrant drive, and 3) to minimize the cost of the lab setup. The only disadvantage is that the motor can only be operated in a single direction.

The 2-quadrant PMDC motor drive circuit is shown in Fig. 6. Though the motor can only be operated in a single direction, students soon understand the need for SW_2 and D_{SW1} in the event that changes in the control signal allow for change in power flow from the motor towards the source. It is a simple matter for students to understanding that the addition of a second half-bridge circuit will extend the two-quadrant drive to the four-quadrant drive. The associated lab exercise requires the student to build the additional circuitry that extends the buck SMPS to the 2-quadrant drive, to measure the 2-quadrant drive efficiency vs. load, and to determine which components contribute greatest to the decrease in efficiency as the load increases (i.e., conduction losses through components, or switching losses in the transistors?). Students also plot the change in duty-cycle with load and realize the need for closed-loop control. Further performance, model parameter accuracy and equivalent circuit model verification concludes the exercise. In their post analysis, a PSpice model of the entire circuit is constructed and simulated for comparison to actual lab data.

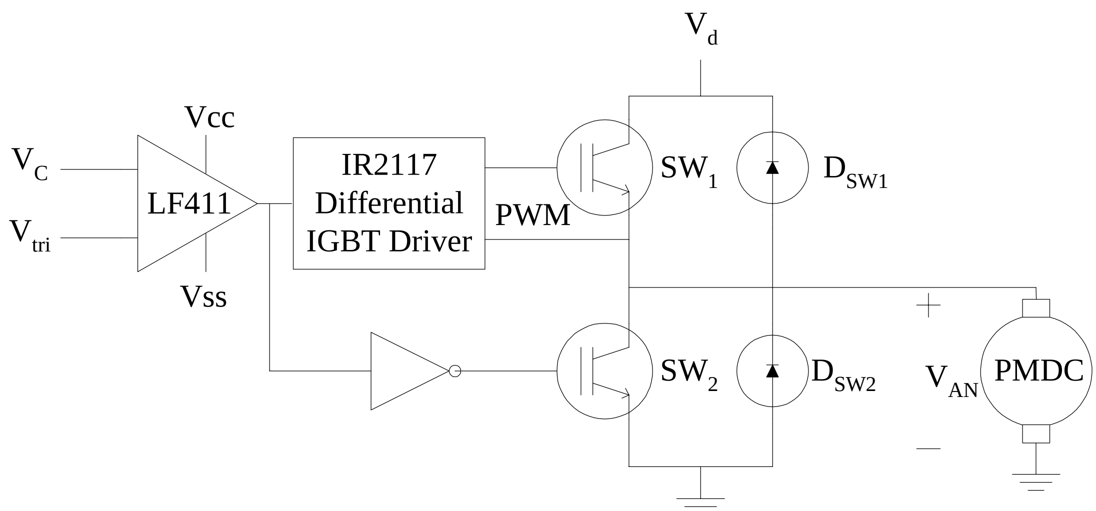


Figure 6: 2-quadrant PMDC motor-drive circuit

This approach provides the student with both a higher-level and lower-level practical approach to the simplicity of the 2-quadrant PMDC motor drive. The combination of Mohan's voltage-to-current port approach and the volt-second approach provides the firm foundation when expanding to polyphase motor drive schemes. Details regarding the associated laboratory exercise can be obtained at the following location:

http://learn.sdstate.edu/shietpas/asee/asee02/lab_7.pdf

A firm understanding of the PMDC, its equivalent circuit model and the 2-quadrant PMDC motor drive provides numerous opportunities to students who wish to pursue design projects that employ a motor drive within the desired application. Section V describes a simple, yet fascinating design project that combines a prime energy source (PV array), motor drive (2-quadrant), motor (submersible pump), and load (water).

V. PV-Operated Submersible Pump System

At this point in the course sequence, students may be encouraged to work in teams on a "simple" design project. One such application is the need for an efficient power source for water well pumps located in remote areas. In remote applications a Photovoltaic (PV) array and battery bank is often selected as the prime power source. A system level design approach should be followed to minimize the number of solar panels needed to operate the submersible pump efficiently. Due to the inherent nature and efficiency of a PV array and the fact that it will need to operate in a wide range of lighting conditions, an efficient electric drive to interface the PV array with the pump is required.

The project selected for our students uses the Siemens PV array SM 110-24, rated for 35 Vdc and the Dankhoff Submersible Solar Slowpump model number 2507-24, rated for 24 Vdc and 8 A input. Following is a suggest list of tasks students should perform in the design of an optimal motor pump drive for this project.

Project Task Outline:

1.) Conduct tests to confirm the performance and the manufacturer parameters of both the PV array and solar pump.
    a. The PV array can be tested in various lighting conditions (both unloaded and nominally loaded). We provide students with a pyranometer and Licor Datalogger that measures light intensity in W/m^2. Output voltage, current and power measurement are easily accomplished using standard laboratory equipment.
    b. The Solar pump can be tested using a bench DC power supply of sufficient size and the Magtrol hysteresis brake dynamometer setup. With a quality oscilloscope and current probe amplifier system, a relatively accurate model of the pump can be achieved.
2.) Size for the appropriate power semiconductor switches and construct a simple 2-quadrant motor drive. Test the motor drive using the bench DC power supply and

resistive loading.

3.) Combine the models of each subsystem (PV array, motor drive, pump, and simple resistive load) into PSpice and simulate to determine the expected system performance. To simplify, assume good weather conditions and nominal loading.
4.) Integrate the entire system hardware and test under actual good weather conditions under nominal loading.
5.) Compare predicted results from simulated data to actual data.

VI. Conclusion

An efficient pedagogical approach has been presented for the integration of power electronics, drives and the PMDC motor. Using a "just-in-time" approach, material is introduced in the course lecture to adequately prepare students in the practical understanding of the PMDC motor, fundamentals of power electronics, and the PMDC motor drive. After a complete model of the PMDC is established, both theoretically and from lab data, parallels between components in the PMDC model are equated to components in the buck and boost converter topologies. In conjunction with the voltage-to-current pole approach by Mohan, the principle of volt-second energy balance is used in the development of the SMPS and the 2- and 4-quadrant DC motor drives. The combined use of each method provides the student a system level and lower level understanding of the electric drive system. Finally, a practical design project, which includes all elements of the EMEC system, was presented. Preliminary results from student feedback are encouraging and indicate that the accelerated approach to understanding the fundamental aspects of machines, power electronics, and drives is feasible.

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