

Power Electronics Control and Sensing Challenges for an S-CO₂ Turbine Power Take-Off

Jason Neely¹, Steven Pekarek², Lee Rashkin¹, James Pasch¹

Abstract

Consistent with their commitment to energy, climate and infrastructure security, Sandia National Laboratories researchers are in the demonstration phase of a novel gas turbine system for power generation, with the promise that thermal-to-electric conversion efficiency will be increased to as much as 50 percent — an improvement of 50 percent for nuclear power stations equipped with steam turbines, or a 40 percent improvement for simple gas turbines. In particular, this larger effort focuses on supercritical carbon dioxide (S-CO₂) Brayton-cycle turbines, which typically would be applied as primary cycles, preferably for closed cycle heat sources such as next-generation power reactors, and as bottoming cycles for other primary cycles and waste heat streams. A major issue of the demonstration system is the design of the power electronics used to convert the AC power from the high-speed permanent magnet (PM) generator to DC power that may be delivered to a load. This paper will discuss the design considerations required to allow for generating and motoring modes of operation and presents a methodology for controlling torque with the DC-AC power electronic controller.

Motor/Generator Description

The Brayton Cycle power conversion system is described in [1]. The machine used in the system is a permanent magnet 2-pole, 3-phase, 24 slot, 75 kRPM machine. The rotor is made of a solid samarium-cobalt (SmCo) permanent magnet material with a relative permeability near unity. The stator coil is made from stranded copper wire, and the three phases are wye-connected with the neutral inaccessible. Pictures of the rotor and stator are shown in Figure 1.



Figure 1. Photos of (left) rotor and (right) stator

¹ Sandia National Laboratories, Albuquerque, NM

² Purdue University, West Lafayette, IN

The electromechanical model is developed assuming a permanent-magnet round-rotor machine, consistent with systems presented in [2].

Principle Components and Drive Control

The power electronic conversion system includes a DC-AC converter and a DC chopper, illustrated in Figure 2. The excitation of the permanent magnet machine is provided by the DC-AC converter. Therein, the 2-level DC-AC converter converts power from DC to AC when operating as a motor drive and from AC to DC when generating. In particular, the AC converter controls the phase voltages v_{as} , v_{bs} , and v_{cs} through gating ‘on’ and ‘off’ the switches T1 – T6 shown in Figure 2. The diodes D1-D6 cannot be directly controlled but play a role in switching. The resulting phase voltages in turn yield phase currents i_{as} , i_{bs} , i_{cs} that produce electromagnetic torque T_e . When generating, the power is converted to DC and then dissipated in the load through the load chopper. Load chopper power is modulated through switching of IGBT TC.

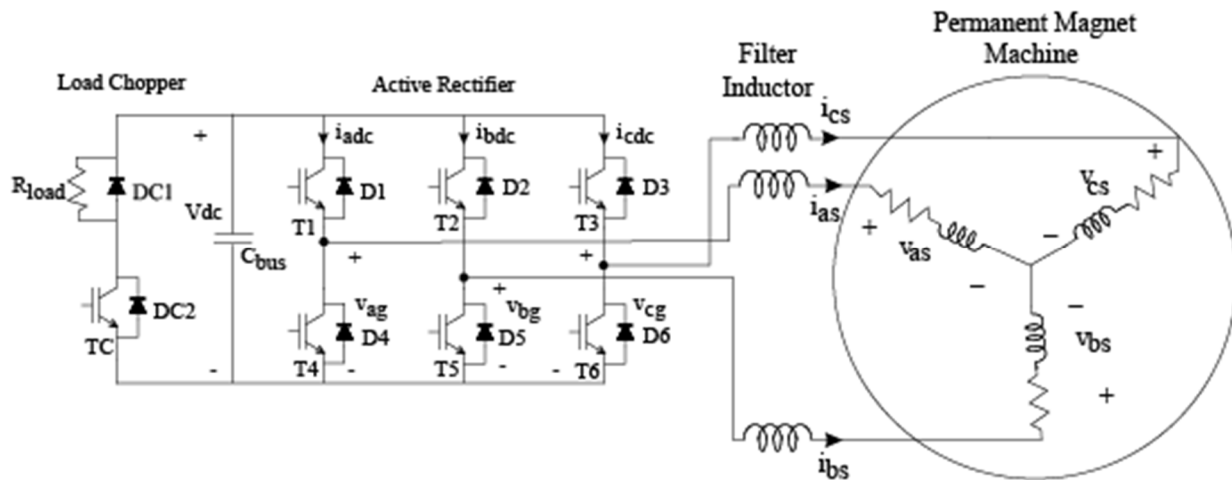


Figure 2. Active rectifier/machine/load chopper.

The system presents several control challenges. In most turbo-machinery systems, throttle control of the prime mover (turbine) is used to control the rotational angular velocity of the electric machine, and the generator/active rectifier is then used to control the dc bus voltage. The use of power electronics to control both a dc bus voltage and a machine speed is atypical. In particular, if the dc voltage and speed are regulated by the same DC-AC converter, both control loops influence the stator currents and electromagnetic torque, resulting in a strong coupling between speed and dc bus voltage. As a result, tuning of the control gains to achieve a stable response over a wide range of loads is a significant challenge. This was observed in system hardware and in simulations of the system for a control developed in an earlier effort. Furthermore, there is no need to implement separate motoring and generating torque control loops as the electromagnetic torque of the machine is controlled the same whether the torque is negative or positive. In the approach proposed herein, standard torque control methods are presented that may be applied identically in both motoring and generating mode. However, as will be discussed, performance depends on reliable measurement of the rotor angle.

Torque Control in Permanent Magnet Machine

Using reference frame theory [2], the machine phase currents i_{as} , i_{bs} , i_{cs} may be expressed in terms of so-called q -axis and d -axis currents i_{qs} , i_{ds} , expressed as:

$$\begin{aligned} i_{as} &= i_{qs}^r \cos(\theta_r) + i_{ds}^r \sin(\theta_r) \\ i_{bs} &= i_{qs}^r \cos(\theta_r - 120^\circ) + i_{ds}^r \sin(\theta_r - 120^\circ) \\ i_{cs} &= i_{qs}^r \cos(\theta_r + 120^\circ) + i_{ds}^r \sin(\theta_r + 120^\circ) \end{aligned} \quad (1)$$

wherein θ_r is the rotor angle, and the q -axis and d -axis stator currents describe the alignment of stator magnetic poles relative to the rotor magnetic poles, as illustrated in Figure 3. The reader is directed to [2] for additional information on reference frame analysis.

The goal of the excitation of a machine, whether motoring or generating, should be to obtain the desired torque from current control. In particular, for round-rotor machines such as the one investigated here, and likely to be used in high-speed turbines, it can be shown that the electromagnetic torque is computed as the following [2]:

$$T_e = \frac{3}{2} \lambda_m' i_{qs}^r \quad (2)$$

where λ_m' is the constant magnetic flux coefficient of the rotor magnet. Only equation (2) is needed for both modes of operation; $T_e > 0$ for motoring and $T_e < 0$ for generating. In an ideal round-rotor PM machine, torque only varies with the q -axis stator current; so, any d -axis current only contributes to electrical loss and potentially magnetic saturation without influencing torque. Thus, to operate at peak efficiency in an ideal round-rotor machine, it is desirable for $i_{ds}^r = 0$ to achieve “maximum torque per ampere.” It is also noted that $i_{ds}^r = 0$ ensures the stator poles are orthogonal to the rotor poles as shown in Figure 3. In realistic systems, however, due to core loss, setting $i_{ds}^r = 0$ will not necessarily result in maximum torque per ampere, but it is still an appropriate approximation.

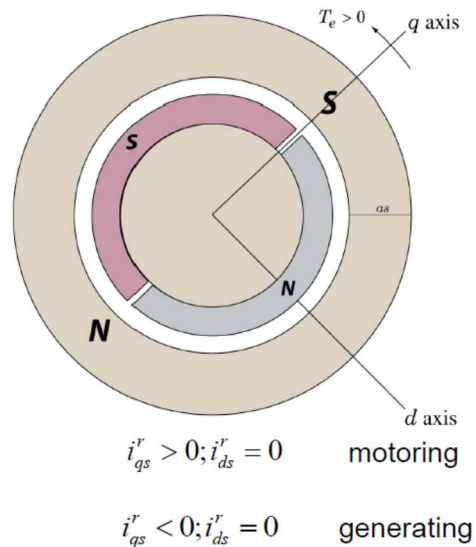


Figure 3. Cross sectional view of machine with stator/rotor poles and torque expressed in terms of rotor reference frame variables.

To achieve the desired torque with approximately maximum torque per amp, switching of the active converter is performed such that:

$$i_{qs}^r = \frac{2T_e^*}{3\lambda_m}, \quad i_{ds}^r = 0 \quad (3)$$

where T_e^* is the commanded torque. In practice, this torque command should be obtained from a controller responding to the error between commanded and measured dc bus voltage. Controlling the DC-AC converter in such a way yields stator currents of the form:

$$\begin{aligned} i_{as} &= i_{qs}^r \cos(\theta_r) \\ i_{bs} &= i_{qs}^r \cos(\theta_r - 120^\circ) \\ i_{cs} &= i_{qs}^r \cos(\theta_r + 120^\circ) \end{aligned} \quad (4)$$

Achieving the stator currents of the form shown in (4) requires switching to obtain the necessary stator voltages. In practice, the control can be expressed in terms of the block diagram shown in Figure 4. Within Figure 4, the starred '*' variables denote commanded values. Specifically, based upon the idea of maximizing torque per amp, a commanded q -axis and d -axis currents are generated from (3). Measured values of i_{qs}^r and i_{ds}^r currents are obtained from the measured stator phase currents. The error between measured and commanded currents is then used to establish commanded stator voltages, v_{qs}^{r*} and v_{ds}^{r*} . The stator voltage commands are mapped to commanded duty cycles

$$\begin{aligned} d_a &= \frac{2}{v_{dc}} (v_{qs}^{r*} \cos(\theta_r) + v_{ds}^{r*} \sin(\theta_r)) \\ d_b &= \frac{2}{v_{dc}} (v_{qs}^{r*} \cos(\theta_r - 120^\circ) + v_{ds}^{r*} \sin(\theta_r - 120^\circ)) \\ d_c &= \frac{2}{v_{dc}} (v_{qs}^{r*} \cos(\theta_r + 120^\circ) + v_{ds}^{r*} \sin(\theta_r + 120^\circ)) \end{aligned} \quad (5)$$

that are compared to a triangle wave to generate the transistor gate commands for T1-T6. It is noted that implementing this control requires careful measurement of the rotor position.

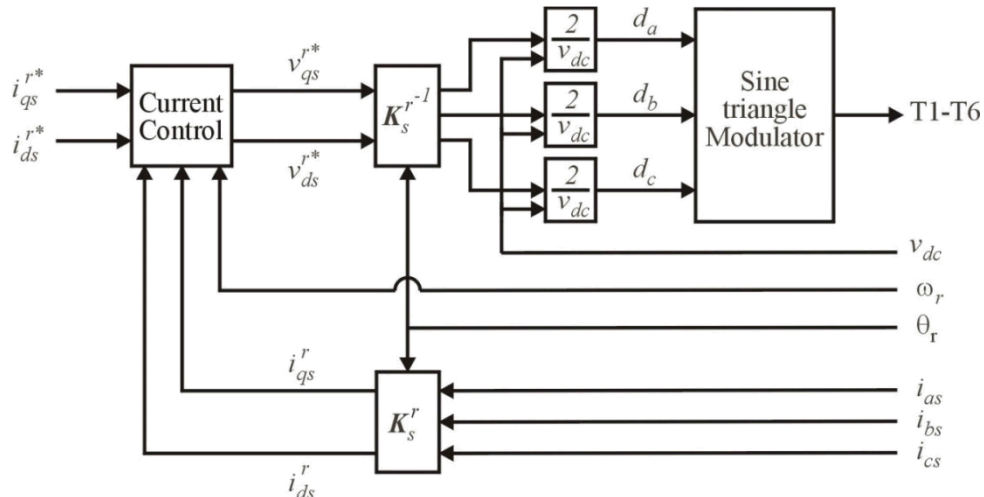


Figure 4. Block diagram of the proposed sine-triangle based current control method [2].

Conclusions and Design Challenges for this Control in SCO2 Applications

When *motoring*, the dc link voltage is maintained by a grid connection and when *generating* the dc link voltage is maintained through torque control. Thus, how the torque command is computed is different in the two modes, but it is not necessary to implement the torque control loop (equation (3) and Figure 4) differently in the two modes. In *motoring*, the commanded torque is positive, resulting in a positive q -axis current. In *generating*, the commanded torque is negative, resulting in a negative q -axis current. This should be done seamlessly without switching between torque control algorithms for the torque control portion.

Simulations have been performed that demonstrate that this control does work within the existing Brayton cycle system wherein the load chopper is used to control speed and the active rectifier is used to control voltage while generating. Indeed, the system was simulated to achieve rated torque at 75,000 rpm. The blocks shown in Figure 4 are readily implemented within a processor (preferably floating point). However, in hardware, attaining an accurate rotor position measurement is challenging.

The SCO2 environment is high-temperature and high-pressure, with materials issues that continue to be explored. Standard optical or hall-effect sensors cannot be co-located with the rotor in this environment. Furthermore, methods such as using a *speed loop* can survive this environment but have presented with other problems. A *speed loop* is an extraneous stator winding that senses the back-emf of the rotor magnet and thus allows for the rotor position to be sensed with precision when there is no stator current. As stator current increases, the speed loop voltage exhibits a phase shift and thus the rotor position calculation begins to accumulate error. Depending on the configuration, this can result in instability as the rotor angle error results in more commanded d -axis current, which in turn causes greater rotor angle error and the process “runs away.” This has been demonstrated in hardware and simulation. As a final remark, it is recommended that a robust rotor position measurement system, such as an optical fiber-based rotor position encoder be implemented in concert with the torque control described herein.

Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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