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ABSTRACT

Due to the need for improving fuel economy, reducing tailpipe emissions and the trend towards increasing electrical content in automobiles, hybrid drivetrains are being considered by the automotive industry. In the foreseeable future, in order to address the drive towards hybridization, vehicle manufacturers will begin to use a 42 volt-based architecture in conjunction with an integrated starter and generator system. Depending on the desired power level and allowable changes to the vehicle drivetrain, either an Integrated Starter Generator which mounts between the engine and the transmission or a Belt Alternator Starter (BAS) system which mounts on the accessory belt can be used.

This paper will examine the impact of choosing either a Permanent Magnet (PM) machine or an Induction machine for a BAS application. The impact of the technology on the electric machine design process, power stage implementation, control strategy and overall system design philosophy will be discussed. Test data for both Induction and PM machines will be presented to help underscore the differences.

INTRODUCTION

A Belt Alternator Starter system is comprised of an electric machine, power electronics, controller, and battery and acts to increase vehicle fuel economy and reduce tail pipe emissions. Improvements of over 10% in fuel economy for city drive cycles have been achieved in vehicles using BAS systems [1], [2]. Figure 1 shows a high level functional diagram of a BAS system. A BAS system takes the place of the traditional generator and starter and is located in place of the generator. Such systems provide the ability to perform engine stop/start, electromechanical launch assist, regenerative braking, high power generation, and other functionality without requiring large changes to the vehicle. These systems can be implemented with several different types of electric machine technologies. The choice of machine technology will determine the required inverter stage of the power electronics, its associated protection circuitry, as well as the machine control strategy. The machine technology will also dictate the achievable system performance in terms of motor/generating efficiency and output power capability.

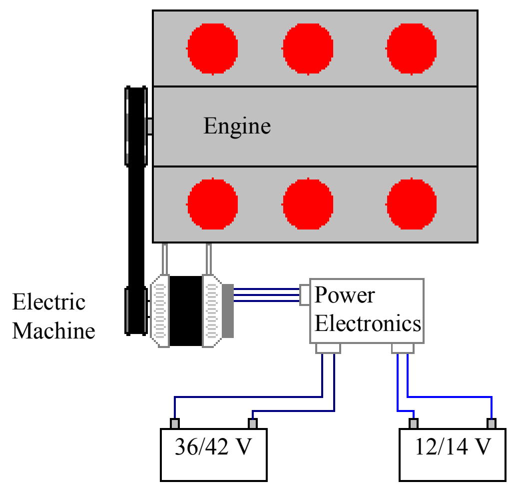

Figure 1 BAS System Architecture

BAS VEHICLE SYSTEM ELECTROMECHANICAL FEATURES

The ability to start the engine quietly and quickly is an important feature of the BAS system. This enables the vehicle to shutoff the engine when idling conditions are fulfilled which saves fuel when the vehicle is not in motion. When the vehicle operator wants to move the vehicle, the system must respond quickly and bring the engine from rest to normal operating speeds in a short period of time. Some BAS systems will delete the cranking motor from the engine system, which will require the BAS system to start the engine even in extremely cold temperatures. The quick starting and cold starting requirements will establish the values for the peak motoring torque and the maximum motoring torque curve for the electric machine. Figure 2 illustrates the desired motoring torque characteristics for the electric machine.

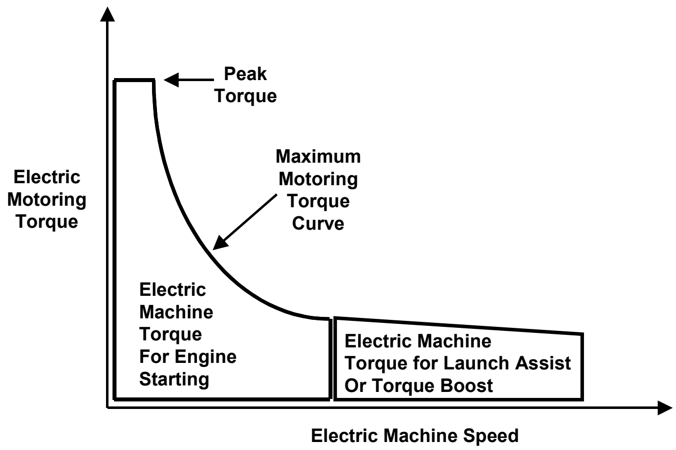

Figure 2 Motoring Torque Requirements

The peak torque value is determined by the requirement for cold starting operation. The values for the maximum motoring torque curve are determined by the time requirement to reach the engine idle speed. The time requirement is in the range of 250 to 400 milliseconds depending on the application. The torque values for performing launch assist or torque boost to the engine are determined from customer requirements. Launch assist torque is supplied from engine idle speed to the speed where the engine can develop higher torque output. This is 2,000 to 2,500 rpm for most gas engines.

The electric machine operates in the generator mode in three principal areas. Figure 3 illustrates the principal operating areas for generating.

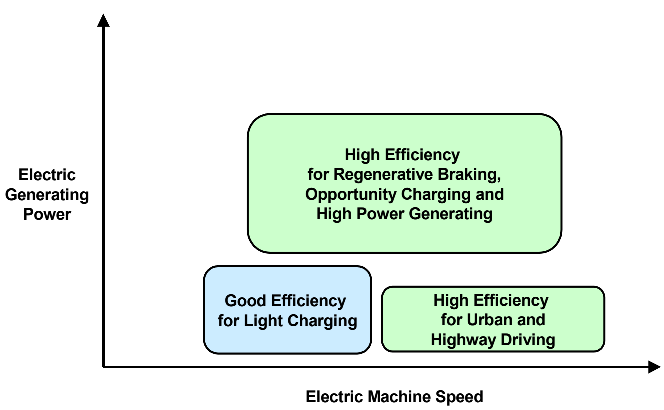

Figure 3 Principal Generating Areas

The areas that require high efficiency during generating are the areas for regenerative braking, opportunity charging, high power generation and highway or urban driving. These principal areas require higher efficiency than is delivered by the conventional 12 V Lundell generator. The generating area at light charging loads in the idle region requires that the generating efficiency be as high as the 12 V Lundell generator. The idle speed area is not used as extensively as with todays vehicle with the ability to shutdown the engine when the vehicle is at standstill conditions.

ELECTRICAL MACHINE DESIGN AND PERFORMANCE CONSIDERATIONS

To achieve the performance requirements dictated by the application, the electric machine must be carefully designed, regardless of the machine technology, permanent magnet or induction. Furthermore, it becomes readily apparent that a system level optimization must take place, trading off the ability of the machine to meet the requirements versus the burden placed upon the power electronics, battery, and machine control system. To meet the design goals, two machines are considered; one machine being a permanent magnet machine and the other an induction machine. The machine size is constrained to that generally allotted to a typical, high output, generator. The machine is to be belt driven with a 2:1 to 3:1 drive ratio similar to a typical generator and is to be air cooled. Each of the permanent magnet and induction machines will be designed to the same peak phase current. The final machine configuration is as shown in Figure 4.

Figure 4 BAS Electric Machine

In an effort to reduce the inverter AC current draw and closely mimic the application requirements, the machine must be designed with a low base speed and a large field-weakened region. The base speed is the speed at which the constant torque region of the torque speed curve ends and full voltage is applied to the machine by the inverter. The region of operation beyond base speed is consequently referred to as the field or flux-weakened region. In this region, the airgap field, or flux, is weakened as speed increases to hold the machine EMF approximately constant, and with a given current, provide approximately constant power.

The field-weakened range, defined as the peak operational speed divided by the base speed, is often difficult to define for BAS applications. This is because the variation in DC battery voltage greatly impacts the machine base speed. As the DC voltage increases so does the machine base speed. When operating in the motoring mode, the battery voltage may be in the range of 30 V, while in the generating mode, the battery voltage is often at 42 V.

In practical application, the speed over which constant power can be provided is from base speed to approximately twice base speed for the induction machine. Above this speed, as dictated by the machine leakage reactances, the machine power output capability drops with increased speed. For permanent magnet machine technology, the theoretical field-weakened range is infinite, contingent upon appropriate selection of design parameters [3], [4]. However, in practice, machines designed for large field-weakened operation introduce other technical challenges. First among the challenges is finding a machine design which produces the relatively high direct axis inductance required to operate over a wide field-weakened range. From [3], it is shown that a theoretically infinite field-weakened range can be attained if the machine parameters are set to be

$$k_e = \frac{V_{ph}}{\omega_b \sqrt{2}} \tag{1}$$

and

$$L_d = \frac{2\, k_e}{P\, I_{pk}} \tag{2}$$

where k_e is the rms phase EMF constant, ω_b is the base speed in radians per second, V_{ph} is the maximum applied rms phase voltage, L_d is the direct axis inductance, P is the number of rotor poles, and I_{pk} is the peak rms phase current.

The high direct axis inductance gives rise to a large armature reaction flux which serves to counteract the magnet flux, and hence "weaken" the airgap field. Unfortunately, methods to increase the motor direct axis inductance often introduce unwanted harmonics into the armature reaction flux waveform. These harmonic fluxes, in turn, induce eddy current losses in the rotor magnets, leading to rotor heating issues at higher speeds, in the field-weakened region. In addition, to create the field-weakening flux, negative direct axis current must be added to the machine. The stator losses as a result of this current tend to decrease the machine efficiency in the field-weakened region, particularly at light generating load points where the power producing quadrature axis current is small, but the field-weakening direct axis current is large, hence resulting in abnormally high stator conductor losses for the small power produced.

This later issue is of concern as a low generating efficiency at light load adversely impacts the overall system efficiency and fuel economy under urban driving conditions. The induction machine does not suffer from this problem since in the field-weakened region, the direct axis current decreases with increased speed to decrease the field flux, whereas for the permanent magnet machine the current magnitude must increase.

Areas where the permanent magnet machine show important system benefits include the ability to provide adequate speed and torque to start the engine. With the generally higher power density of the permanent magnet machine [5] – [8], higher torque can be provided, more efficiently, from the same size package. To further constrain the problem, the amount of power that can be supplied from the battery during starting is limited by the battery size and technology. Thus, as the battery power limit is reached, the technology which is more efficient can provide more power to the engine load during starting. Given these constraints, the permanent magnet system is more efficient at low speed, high torque operating points and can supply significantly more power to accelerate the engine up to speed.

The resultant system motoring torque versus speed curves are shown in Figure 5. The test data are representative of torque and speed at the crankshaft, with electrical power sourced from a 42 V battery. From the data, one can see that the permanent magnet system provides significantly higher torque, over much of the speed range of interest, for cranking and accelerating the engine up to idle speed.

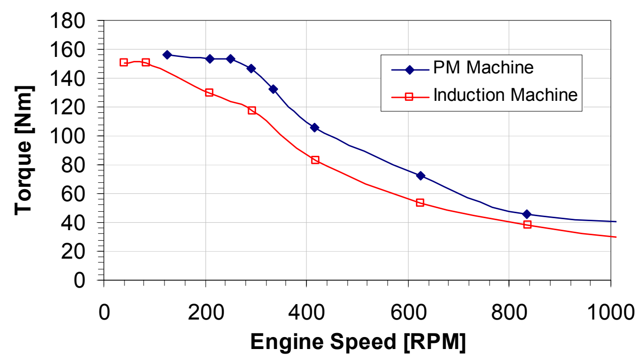

Figure 5 System Starting Torque Test Data

BAS ELECTRIC MACHINE CONTROLLER DESIGN CONSIDERATIONS

As mentioned previously, the BAS system provides the capability for engine cranking, generating, torque boost, launch assist, and low speed crankshaft position control. In order to design a machine controller, it is necessary to consider the appropriate variables to control. At low speeds, the controller is a speed-base system as cranking and engine braking often have desired speed profiles to be followed. A controller that has an outer speed loop with an inner torque control can be used to create this functionality. In addition, torque boost and launch assist functionality are torque-based commands as the powertrain controller is commanding the desired torque to be added from the electric machine to the driveline. Generating, by contrast, is more naturally a power-based command for charging but can be controlled indirectly through torque.

In order to achieve the desired machine and driveline performance, it is clear that torque control is necessary. Ideally, the BAS control system would instantaneously provide the commanded torque under any operating condition, up to the capability of the machine, and as efficiently as possible. Unfortunately, machine performance and capability are a function of a myriad of variables. Available battery voltage, the temperature of the machine, and the speed of operation are the significant variables that must be considered. In a BAS application, these variables can change considerably. Operating voltages for the system will vary from approximately 18 to 48 V and the temperature of the machine can vary from –40 to 150°C. In addition, once the engine has started the machine speed is set by the engine and appears as a disturbance to the machine controller that must be responded to in order to maintain the desired torque. In the case of a BAS system, the speed disturbance to the controller can be extreme due to the belt pulley ratio which means that the acceleration will be 2 to 3 times faster on a BAS system than on a crank-based system. To illustrate this point, an unfueled crank event on a V-6 engine using an Induction BAS system is shown in Figure 6.

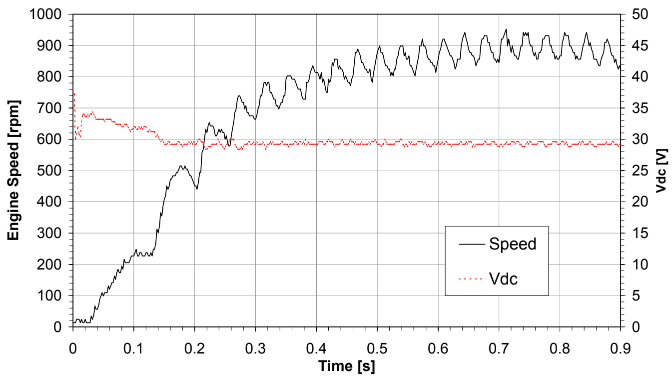

Figure 6 Engine Crank with a BAS Induction Machine Showing Battery Voltage and Machine Speed

Figure 6 shows how quickly the machine accelerates the engine and how quickly the battery voltage can change. Large variations in the battery voltage are possible since the battery capacity is generally rather small in these systems. Even with a charged battery, the voltage drops down to 29 V during the crank event immediately after torque is applied to the machine and again after 200 ms of cranking. The ripple on the machine speed that is apparent in the figure is due to engine compression events. The acceleration during these events is considerable. Compensation for the fluctuation in these variables must be made for a successful system implementation that creates the highest efficiency and torque capability.

A general description of the controller can be made without specifying the machine technology based on the controller goals outlined above. To meet the expected torque performance at low speed, a current controller is required. In the low speed constant torque region, the current regulator will naturally compensate for variations in battery voltage levels and engine speed fluctuations. Given that the battery voltage and temperature influence the point where full voltage is required and determine what torque is attainable, compensation for these variables is essential. Furthermore, given that the peak engine speed can exceed 6,000 rpm with the machine fundamental frequency at 1,000 Hz or more, voltage control techniques can be utilized at higher speeds if current regulation becomes problematic. This strategy also has the advantage of providing the full available voltage without leaving any margin for controllability.

INDUCTION MACHINE CONTROL

For an induction machine, vector control is an effective underlying strategy for this application. In order to achieve the desired torque control the rotor relative position, or speed, is required. This can be achieved by either sensorless methods or a sensor. If a sensor is used then a relatively low-resolution sensor with appropriate processing strategies to achieve the desired performance is possible in order to reduce cost. Torque control strategies that use full voltage and slip control can be used at higher speeds and for torques that require full voltage. This approach can optimize both efficiency and torque capability.

One of the specific issues that must be addressed with an induction machine is the effect of bus voltage variation. It can be shown that the peak torque available, neglecting saturation effects, is related to the available voltage squared. Furthermore, the point where the field-weakened region starts is a function of the requested torque, temperature and the available voltage. Figure 7 shows the torque capability of a BAS induction machine as a function of speed, battery voltage and temperature.

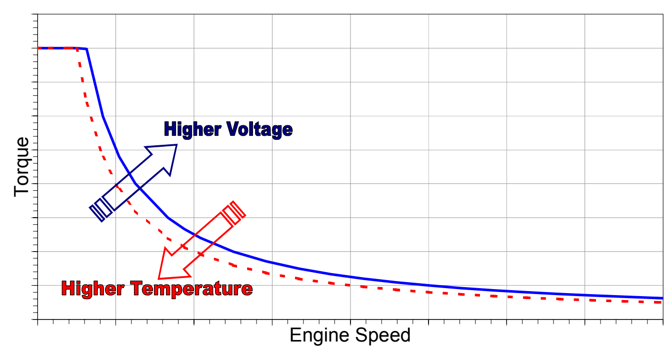

Figure 7 Torque capability of BAS Induction Machine Showing the Effect of Battery Voltage and Temperature

Considering Figure 7, it is apparent that there is a small constant torque region. In this region, the vector controlled induction machine is insensitive to voltage variations as the current controller naturally corrects for these effects. Temperature variations exist in this region but through proper slip gain correction, this variation can be largely eliminated. Therefore, the current commands to the induction machine will not change. Above this region, however, the current commands become dependent on voltage and temperature fluctuations which vary independently. In addition, the peak torque capability of the machine can be seen to vary as voltage and temperature change.

Figure 8 shows the d and q axis current commands that must occur to achieve the desired insensitivity to voltage and temperature variations. If these variables are not accounted for properly then either loss of control will occur or the efficiency and peak performance of the system will be reduced.

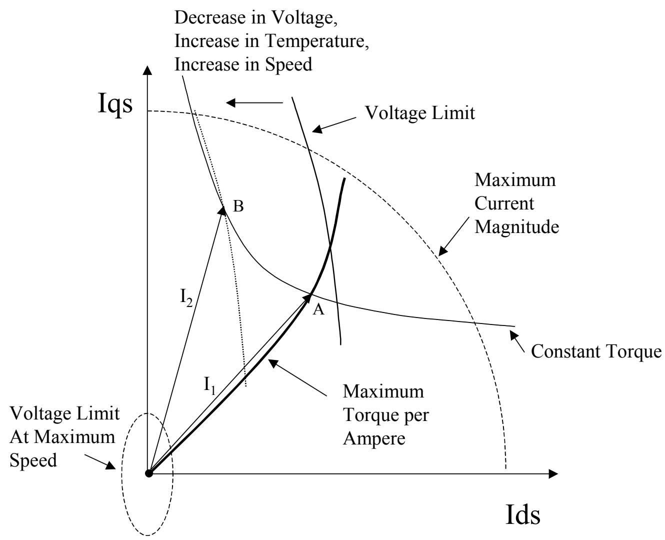

Figure 8 Iqs & Ids trajectory for Constant Torque of BAS Induction Machine

Figure 8 shows the path that current must follow to hold torque constant with optimum efficiency. For each torque level, a constant torque locus can be determined. At low speed, the current regulator follows the maximum torque per ampere curve to achieve the desired torque. The impact of battery voltage, machine temperature and machine speed changes can be shown as a family of elliptical limit curves [9]. For a reduction in battery voltage or for increases in speed or temperature, the effect is to reduce the size of the ellipse and limit the current commands. In the figure, current vectors I_1 and I_2 achieve the same torque but I_2 must be selected when the effect of voltage, temperature or speed limits the allowable vectors. It is important to note that the effects of voltage, temperature and speed are separate but act in a similar fashion in changing the elliptical limit. At extreme speeds or low voltages, the allowable currents become very small and ultimately limit the torque capability of the machine.

With the induction machine, there is also an issue associated with the trade-off between optimal torque response and optimal efficiency. If a fast torque response is desired, the machine flux is left unchanged so that the rotor time constant circuit is not affected. This condition means that non-optimal flux is operated in the machine with its associated losses. For optimal efficiency operation, it is necessary to change the flux when the torque command is changed. When the flux level is changed, the torque response is not instantaneous and an inherent delay related to the rotor time constant will occur before the desired torque is reached. Depending on the region of operation, either strategy may be appropriate. For instance, during low speed operation, a fast response may be required in order to meet cranking time requirements whereas for higher speeds in the generating region the more efficient strategy is desired.

PM MACHINE CONTROL

Similar to an induction machine, current regulation is a natural low speed control strategy for a PM machine. Unlike the induction machine, a Brushless DC (BLDC) mode of operation is possible. With careful control strategy development, this mode of operation can be used with a relatively simple position sensor to achieve the desired low speed performance while still allowing the use of vector control strategies at higher speeds. With appropriate controller design, these modes can be used in conjunction with each other. The BLDC mode can be used from standstill and for part of the low speed region due to its simplicity and robustness while vector control can be used to achieve the desired high speed field-weakened performance. Figure 9 shows a machine phase current from an engine crank using this concept with a PM BAS machine. From the figure, the BLDC mode of operation and the transition to sine mode of operation can be seen. As a note, the change in amplitude is directly related to the change in the commanded torque during the crank event.

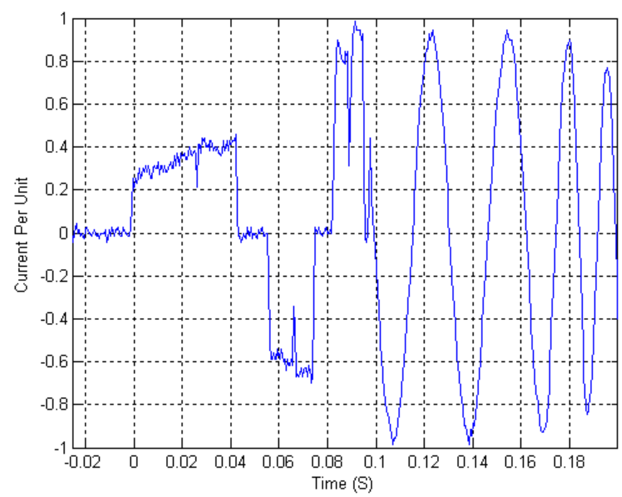

Figure 9 Phase Current of PM Machine During Engine Crank

The PM machine also has a high speed full voltage control mode although this is based on the control of the angle between the machine's EMF and the applied voltage. Unlike the induction machine, there is critical speed where full voltage is required to produce any commanded torque in the machine so only the angle must be controlled. Finally, the PM machine has a naturally fast response as the flux is already established in the magnet and does not have to be induced through a coupling from the stator and rotor circuits.

The PM machine has its own unique challenges that must be addressed in order to achieve the desired performance goals. Temperature compensation is more critical in a PM machine as the machine's rotor flux is strongly dependent on temperature. Figure 10 shows the effect of temperature on the performance of a PM BAS machine.

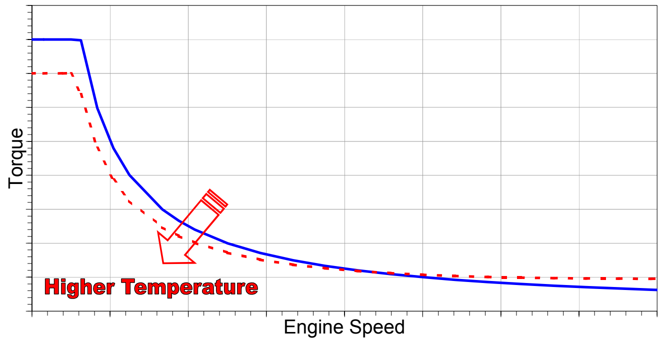

Figure 10 PM BAS Torque Characteristics as a Function of Speed, Voltage and Temperature.

From Figure 10, it can be seen that unlike the induction machine, temperature must be considered in the constant torque region. This sensitivity is due to the dependence of magnet flux strength on temperature. In the field-weakened region, there are significant differences in machine capability which means that the current commands will vary significantly with temperature.

Similar to the induction machine, the PM machine control is affected by the available voltage. The effect of lower voltage is to reduce the speed range of the constant torque region. In the field-weakened region, the peak performance, in terms of torque production and efficiency, decreases with lower voltage. The current commands to the machine must therefore be adjusted with the voltage to ensure that optimal efficiency is achieved and that the peak torque capability is available. Figure 11 shows how the optimal commands must change.

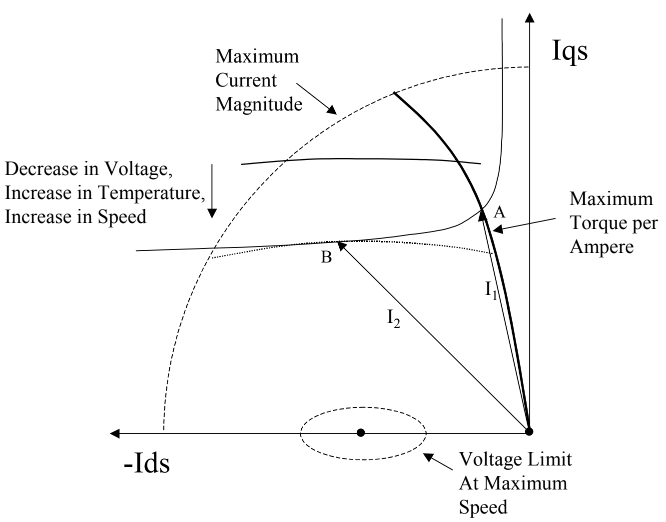

Figure 11 Ideal PM Current Command Trajectories

As with an induction machine, the impact of voltage, temperature and speed on the controller can be shown as a family of ellipses. These ellipses represent limits to the allowable current vectors. At low speeds, the optimal commands will follow the optimal torque per ampere trajectory until the limit of the inverter's current limit is reached or until the controller is limited by an ellipse. Therefore, the peak achievable torque will vary in the machine based on whether the limit is due to a voltage, temperature or speed constraint. Furthermore, in order to maintain a given torque the current vector will need to shift. In this example, the vector I_1 is the optimal point when the system is not limited but the vector will need to change when a limit is reached. In this example, the intersection of the constant torque locus and the elliptical constraint show that the vector I_2 would be required if torque is to be maintained. Note, I_2 is larger in magnitude than I_1 as it is now requiring extra direct, or field-weakening, current.

PM machines also have a more stringent position-sensing requirement. Since the rotor flux is already established in the magnet, the controller must detect its position and track it. Therefore, absolute position of the rotor is required. Again, sensorless or sensor-based techniques can be used depending on the complexity allowed and performance desired from the system. A low cost sensor consisting of hall effect or magnetoresistive elements combined with a low tooth target wheel and appropriate processing algorithm can radically reduce the sensor cost while still providing the performance required to control the machine across the operating region of the application.

The PM machine also is subject to overvoltage issues associated with field-weakened operation [10]. As the speed is increased in the field-weakened region, a condition will occur whereby the induced voltage from the magnets will equal the applied voltage from the inverter. For every speed higher, the induced voltage exceeds the applied voltage and only through applying flux-weakening current is control maintained. In field-weakened operation, a current is applied that spatially acts to create a flux to oppose the magnet's flux. If for any reason this current is not applied, the full induced voltage of the machine will be applied to the power electronic stage. If a standard inverter is used with parts rated for the application then the inverter can be destroyed. One option is to design an inverter with parts rated for the highest machine induced voltage anticipated. Unfortunately, while being the simplest approach, this is a costly solution. Alternatively, approaches that short circuit the machine that inherently protect the inverter are more appropriate but subsequent machine thermal issues may result without careful design.

CONCLUSION

Design considerations for BAS systems have been presented and discussed for both induction and permanent magnet technologies. Two systems, induction and permanent magnet, were built and tested and the results summarized in the paper. Test data has also been presented showing both the system capabilities and the control complexities of each technology.

Many of the design considerations center around the differences in the technology. From the machine standpoint, the limitations in adequately operating either machine over a large field-weakened range were highlighted. The induction machine's limitation is associated with a loss of high speed power while the permanent magnet machine's limitations are associated with high speed, low power efficiency concerns and potential high speed thermal issue. Both machines were found to provide adequate power for quick acceleration of engines over a wide temperature range and more than sufficient generating power.

From the machine control perspective, the many operating control modes required by the BAS application were introduced and explained. Such operating modes were shown to be necessary to meet the demanding application requirements while also serving to maintain a low overall system cost. Additionally, the need for voltage and temperature compensation to provide the required performance at the optimal efficiency was demonstrated for each technology. With both the induction and permanent magnet system technologies showing benefits in differing areas, it ultimately comes down to the needs and desires of the system integrator to determine which technology is appropriate for a given application.

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