System Considerations in the Operation and Control of an Integrated / Starter Generator

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ABSTRACT

Various system level characteristics and parameters must be considered when incorporating an Integrated Starter / Generator (ISG) into the electrical architecture of a ground vehicle. Three techniques will be discussed in the context of system level performance and efficiency. Dynamic Field Weakening will be discussed as a method to shift the operating envelope of the machine / drive pair to dynamically manage operating efficiency with experimental data shown. Pulse Width Modulation – Rectification / Control (PWM-RC) during generation mode will be with simulated and experimental results presented. Finally, the impact of low winding inductance machines, such as air core or iron-less, when operated in a field weakening mode will be discussed along with simulated operation.

INTRODUCTION

Addressing the ever increasing power need from the introduction and transition of next generation equipment and capabilities while supporting a rapid transition between activities without loss of tempo requires new electric power technologies. Tactical electric power must enable a soldier's ability to dominate by providing maximum combat power to these new electric loads when needed with minimal logistics footprint. A 2001 study of mobile electric power technology listed the following requirements [1].

a. Power in the range 0.5 – 20 kW.
b. Electrical power on demand
c. Weight and volume reductions over current technology.
d. Reduction of visual, acoustic, and infrared signature.
e. Scalable in power rating

Integrated Starter / Generators (ISG) and integrated starter / alternators have been proposed as an option to meet the growing electric power needs of passenger and commercial vehicles. Application of an ISG to these vehicles has the added benefit of combining the functionality of the starter and traditional belt-driven alternator into a single unit. Typical machines configured as ISGs are sized in the hundreds of watts to a few kilowatts. Parallel drive trains of Hybrid Electric Vehicles (HEV) are similar to ISG configurations, but at higher power levels. An ISG parallel hybrid electric drive train can be derived from the traditional parallel hybrid by relocation of the clutch [2]. The topological differences are shown in figure 1.

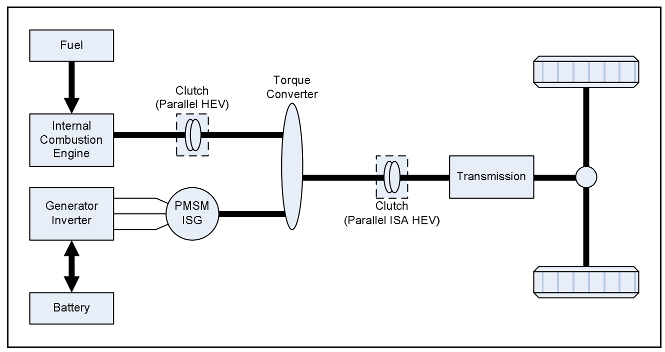

Figure 1: Traditional and ISG parallel HEV drive

Various machine types have been previously studied for application as an ISG. Control of an induction generator configured as an ISG was researched with good voltage regulation and speed range [3]. Wound rotor synchronous machines when operated as ISGs were found to exhibit higher efficiency than induction machines without the need for the wide field weakening zone of Permanent Magnet Synchronous Machines (PMSM) [4]. However PMSM type ISGs are able to achieve the efficiency of wound rotor synchronous machines while providing equivalent power in a smaller size. The primary disadvantage of PMSM type ISGs is the need for active field weakening control at high speeds to prevent over voltage conditions [5]. PMSM type machines' smaller size is due to their inherently high torque density that leads to reductions in size and weight for a given torque output [6]. Due to the PMSM machines higher torque density and power density, it is chosen as the basis for discussion in the remainder of this paper. Other machine types are subject to similar system considerations with varying impact.

Addition of an ISG to a tactical or combat vehicle creates a mobile electric power system capable of addressing the five requirements identified by TRADOC. Power derived from the ISG is only limited by the internal combustion engine of the vehicle and is scalable from a few hundred watts to the practical maximum for the engine. Power on demand is satisfied by simply cranking the engine. Signature of the mobile electric power system is masked by the host vehicle. Size and weight reductions are ultimately functions of voltage regulation, efficiency and machine winding inductance.

This paper will discuss the system level considerations in the application of Dynamic Field Weakening (DFW) and Pulse Width Modulation-Rectification / Control (PWM-RC) to PMSM type ISGs as well as the impact of winding inductance to system operation. The second section of this paper presents the mathematical model which serves as the background and basis for discussions in following sections. The third section presents detailed discussion with respect to the three issues under consideration. Simulated and experimental results are given. Finally, a short summary of results from the simulations and experimental results is provided.

PERMANENT MAGNET SYNCHRONOUS MACHINE MODEL

PMSM type machines are very similar to wound rotor synchronous machines. In PMSM machines the rotor field is generated by the permanent magnets as compared to the field winding of the wound rotor machine. In addition, PMSM machines do not include a damper winding. The dynamics of a PMSM can be modeled by removing the damper winding and field current dynamics from a traditional wound rotor synchronous machine [7]. When modeled with *abc* phase variables, the machine winding inductances vary sinusoidally with rotor position. Application of a change of variable coordinate transformation to a reference-frame synchronously revolving with the rotor results in winding inductances constant in value [8]. The synchronously revolving frame is denoted as the d, q frame with the d axis aligned with the rotor magnetic field and the q axis leading by 90° electrical. Transformation of voltage and current values for the *abc* to the d, q frame are governed by equations (1-3) with θ defining the angle between the q axis and the a phase magnetic axis.

$$\begin{bmatrix} v_q & v_d & v_0 \end{bmatrix}^{\mathrm{T}} = \mathbf{K} \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^{\mathrm{T}}, \qquad (1)$$

$$\begin{bmatrix} i_q & i_d & i_0 \end{bmatrix}^{\mathrm{T}} = \mathbf{K} \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^{\mathrm{T}}, \qquad (2)$$

and

$$\mathbf{K} = \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin(\theta) & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}. \qquad (3)$$

With these transformations of voltage and current and assuming saturation is neglected, the back is sinusoidal, and eddy currents / hysteresis losses are small, the electrical dynamics can modeled as in equations (4-5) [9].

$$v_d = Ri_d + \frac{d}{dt}(L_d i_d) - \omega_r L_q i_q \qquad (4)$$

$$v_q = Ri_q + \frac{d}{dt} L_q i_q + \omega_r (L_d i_d + \lambda_{af}) \qquad (5)$$

In these equations, R represents the phase winding resistance, ω_r is the rotor angular velocity, λ_{af} is the permanent magnet mutual flux linkage, and L_d and L_q represent the d and q axis inductances respectively. Furthermore, the electric torque crossing the machine's air gap is given by (6),

$$T_e = 3P\left(\lambda_{af} i_q + (L_D - L_q) i_d i_q\right)/2 \qquad (6)$$

where P is the number of magnetic pole pairs.

SYSTEM CONSIDERATIONS

Dynamic Field Weakening

One popular way of controlling PMSM type machines is to hold the d axis current at 0. (6) reduces to (7) when the PMSM is controlled in this way and results in machine torque being proportional to q axis current.

$$T_e = 3P\lambda_{af} i_q / 2 \qquad (7)$$

Solving (4) for the time derivative of i_q yields

$$\frac{d}{dt} i_q = \frac{1}{L_q}\left(-Ri_q - \omega_r \lambda_{af} + v_q\right); \qquad (8)$$

which shows the applied q axis voltage must exceed the back emf term, $\omega_r \lambda_{af}$ which is proportional to speed, by at least the q axis ohmic loss to produce a change in i_q.

Without the ability to affect change in i_q, the machine torque, T_e, is no longer controllable. As v_q is a function of power converter bus voltage, there exists a maximum voltage $v_{q\_\max}$ that can be applied to the machine windings. Machine torque can be controlled at the maximum rated value, $T_{e\_\max}$ and corresponding $i_{q\_\max}$, below a speed given by

$$\omega_{r\_\text{bus}} = \frac{v_{q\_\max} - Ri_{q\_\max}}{\lambda_{af}}. \tag{9}$$

Above this speed $v_{q\_\max}$ remains constant and machine torque is limited to

$$T_e = \frac{3P\lambda_{af}}{2}\left(\frac{v_{q\_\max} - \omega_r \lambda_{af}}{R}\right). \tag{10}$$

In addition the rated power for a machine should not be exceeded by operating at rated max torque above rated base speed. Figure 2 shows a representative maximum torque vs. speed envelope for a typical PMSM ISG and several curves corresponding to different values of operating bus voltage defining the limited operating envelope.

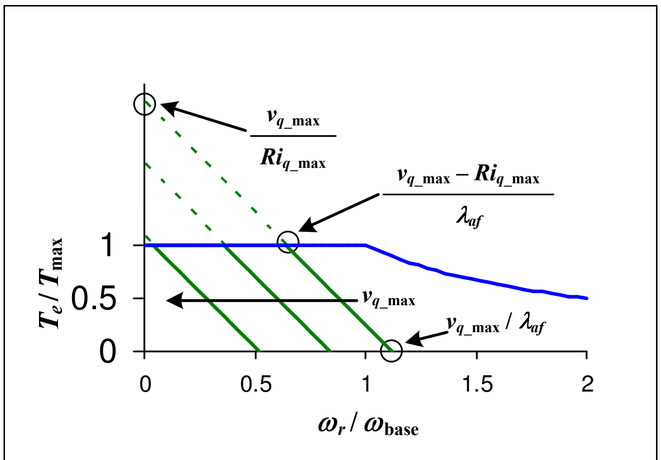

Figure 2: PMSM Operating envelope considering converter voltage and max power curve.

The slope of the torque-speed envelope edge due to converter bus voltage limitation is

$$\frac{\Delta T_e}{\Delta \omega_r} = \frac{-3P\lambda_{af}^2}{2R}. \tag{11}$$

If extended back to zero speed the operating envelope edge from bus voltage limitation would intercept the torque axis at

$$\frac{v_{q\_\max}}{Ri_{q\_\max}} \tag{12}$$

times the rated maximum torque. These lines are analogous to torque-speed curves for a brushed permanent magnet machine supplied from a variable magnitude source. The permanent magnet mutual flux, λ_{af}, is the most significant machine parameter influencing the portion of the torque speed envelope available for a given operating bus voltage. To produce torque beyond the previously discussed bus voltage based limit, the magnetic field generated by the stator winding currents must interact with the rotor permanent magnets' field to yield a net reduction in $\omega_r\lambda_{af}$.

Recalling the orientation of the d, q axis system, field weakening is affected by the controlled introduction of a negative magnitude current oriented along the d axis. Many methods have been researched to affect field weakening. [10]. The simplest is to use the field weakening current i_d to limit the back emf voltage increase above a preselected value. Study of (5) shows i_d can be used to reduce $\omega_r\lambda_{af}$ for speeds above a selected speed, ω_{fw}. The necessary current command to produce the required reduction in $\omega_r\lambda_{af}$ is

$$i_d = \left(\frac{\omega_{fw} - \omega_r}{\omega_r}\right)\frac{\lambda_{af}}{L_d}. \tag{13}$$

Substitution of (14) into (5) gives

$$v_q = Ri_q + \frac{d}{dt}L_q i_q + \omega_{fw}\lambda_{af}. \tag{14}$$

With id no longer held at 0, (7) is no longer strictly true. However, for surface mount PMSM machines the d and q axis inductances are typically close in value and (7) remains valid to approximate the machine torque. The field weakening shifts the maximum operating speed for the machine. The field weakening current requires a corresponding voltage that must be considered against the maximum available from the converter or motor drive. The voltage magnitude applied to the machine windings is

$$v = \sqrt{{v_d}^2 + {v_q}^2}. \tag{15}$$

By substituting (4) and (5) into (15), setting $i_q = 0$, letting $v = v_{\max}$, and solving for ω_r results in the maximum operating speed for the machine given a combination of maximum voltage and field weakening current.

$$\omega_r = \frac{\sqrt{{v_{\max}}^2 - R^2 {i_d}^2}}{\left(L_d i_d + \lambda_{af}\right)} \qquad (16)$$

Ensuring the denominator of (17) remains positive requires

$$-i_d < \frac{\lambda_{af}}{L_d}, \qquad (17)$$

which limits the maximum level of field weakening and may be the governing limit for maximum speed for some machines.

Previously the torque speed envelope was generated in part by limiting operation to regions with q axis current less than the rated value for the machine. The introduction of field weakening current necessitates consideration of the maximum converter current. Given a maximum converter current, $i_{q\_\max}$, and field weakening current set by (13), the converter torque limit due to winding current limitation is

$$T_{\text{current}} = \frac{3P\lambda_{af}}{2}\sqrt{{i_{\max}}^2 - \left(\frac{\omega_{fw} - \omega_r}{\omega_r}\right)^2 \frac{{\lambda_{af}}^2}{{L_d}^2}} \,. \qquad (18)$$

Substitution of $v_{\max}$, (4), (5), and (13) into (15) allows the torque producing current i_q and speed to be related for a given maximum converter voltage. For field weakening operation governed by (13) the field weakening current increases as the operating speed increases. The increase in d axis current results in a lower power factor for the back emf source and higher losses in the power converter due to the current magnitude.

Presented below are maps of efficiency vs. speed and torque. These maps are generated by driving the system under test to torque/speed operating points throughout its entire operating region, and measuring efficiency in mechanical steady state at each point. In this process, the limits of the intermittent operating region of the system are also determined. Tests were performed on a commercially produced PMSM and drive coupled to a four-quadrant dynamometer. The efficiency map shown in figure 3 was generated using field weakening parameters such that the controller begins applying field weakening current at 1300 RPM.

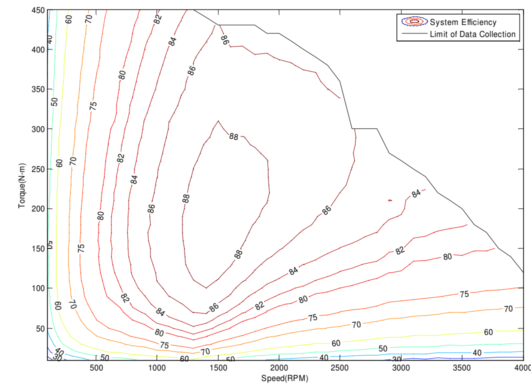

Figure 3: Efficiency map with ω_{fw} = 1300 RPM.

The second efficiency map shown in figure 4 was generated using field weakening parameters such that the controller begins applying field weakening current at 1800 RPM. With the change in speed where field weakening begins the peak efficiency for this machine / drive combination is increased. In addition the region of high efficiency is shifted to higher speeds and higher torque.

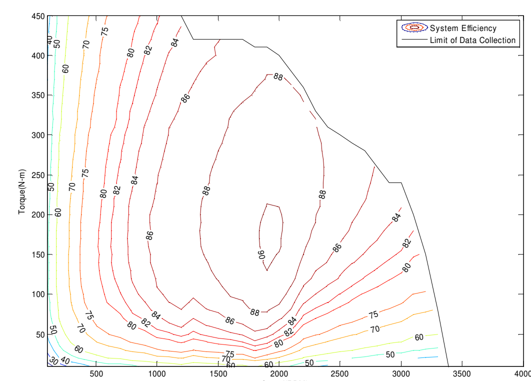

Figure 4: Efficiency map with ω_{fw} = 1800 RPM.

Pulse Width Modulation – Rectification / Control

When integrated into a tactical or combat vehicle to form a mobile electric power system, the ISG can be directly loaded without active control or conditioning. The combined impedance of the machine windings and the load will determine the power factor of this passive system. The presence of reactive power in the system due to the nonunity power factor leads to additional ohmic losses and larger system components to deliver the equivalent real power when compared to a system operating at unity power factor.

Systems with an ISG and passive electrical interactions are subject to two additional factors beyond power factor considerations. First, operating voltage supplied by the ISG to electrical loads in the system will be variable with engine speed and load power. Voltage output from the generator is proportional to engine speed under no load conditions. When loaded the ISG output voltage is decreased due to the internal drop across the winding impedance. The wide dynamic range of operating voltage necessitates utilization loads with exceptionally compliant input requirements. The second, non-power factor, concern when passively interacting with the ISG is energy storage requirements. When the ISG output is passively rectified it will provide power to the system when engine RPM are sufficiently high to generate a voltage larger than present on the energy storage. When these conditions are not satisfied the energy storage components will supply power to the system. The energy storage system will be required to be sized to allow these excursions and keep the operating voltage within the desired range.

Pulse Width Modulation – Rectification / Control (PWM-RC) is a control technique for conventional three-leg power electronic converters conditioning and regulating the output of the ISG. As an active method of interacting with the ISG, PWM-RC overcomes the shortcomings of passive methods. The technique provides the capability to dynamically boost the ISG voltage when the engine is running at a low RPM and limit the voltage at high RPM while regulating the operating voltage over the entire RPM range. PWM-RC actively interacts with the ISG in field enhancement mode at low speeds and field weakening mode at high speeds.

The PWM-RC algorithm under consideration is based upon an "inner loop"/"outer loop" control method [11]. The block diagram of this model is shown in figure 5.

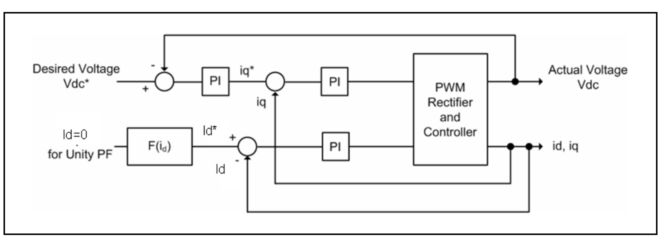

Figure 5: PWM-RC block diagram.

The algorithm uses an "inner" current loop governing the q axis current, relating to the "real" or torque producing current, and the d axis current, which relates to the "imaginary" power. When the ISG is operated at speeds where the no-load ISG voltage is below the desired operating voltage the d axis current is 0 to maintain unity power and maximize system efficiency. For speeds where the no-load voltage exceeds the desired operating voltage i_d is controlled to weaken the rotor field and limit the operating voltage. For the entire speed range the q axis current, i_q, is controlled to regulate the operating voltage.

A simulation of the PWM-RC algorithm was developed to verify the algorithm. Since "real" hardware (machine) and data were available, the motor model was first developed and verified. The motor model was simulated using passive rectification and compared with actual data taken during characterization of the machine. With the motor model verified, an open loop PWM-RC simulation that allowed the q axis (torque producing) current and the d axis (reactive power) current to be input at variable speed and variable load was developed. This simulation diagram is shown in figure 6.

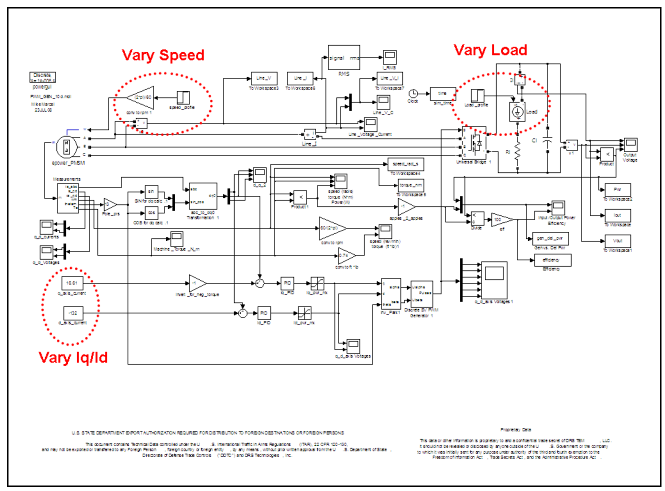

Figure 6: Open loop PWM-RC simulation diagram.

After validation of the open-loop simulation, the full PWM-RC controlled ISG system was simulated as a closed-loop representation of the algorithm to be implemented in hardware. The simulation regulates to a desired bus voltage and allows controlled variations in speed (either constant speed or step speeds) and controlled variations in load (either constant load or step load). Other variables that may be of interest are the PID constants in the inner loops or outer loops and current limits. Figure 7 shows the simulation of the closed loop algorithm.

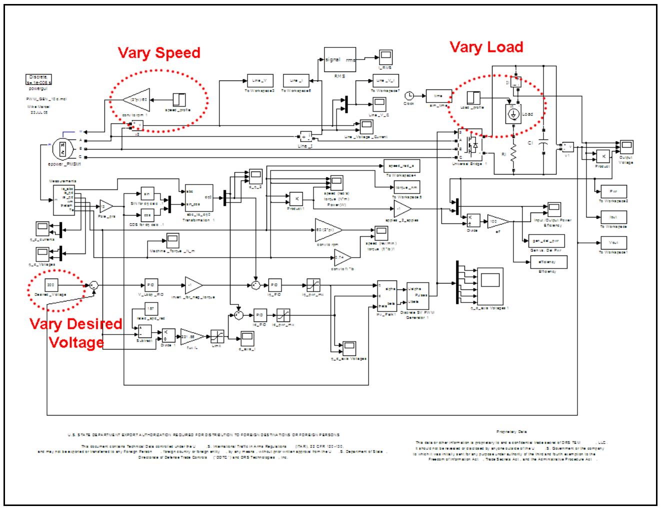

Figure 7: Closed loop PWM-RC simulation diagram.

Various test cases were run using the PWM-RC simulation. Figure 8 shows the results of one simulation run at 800 RPM.

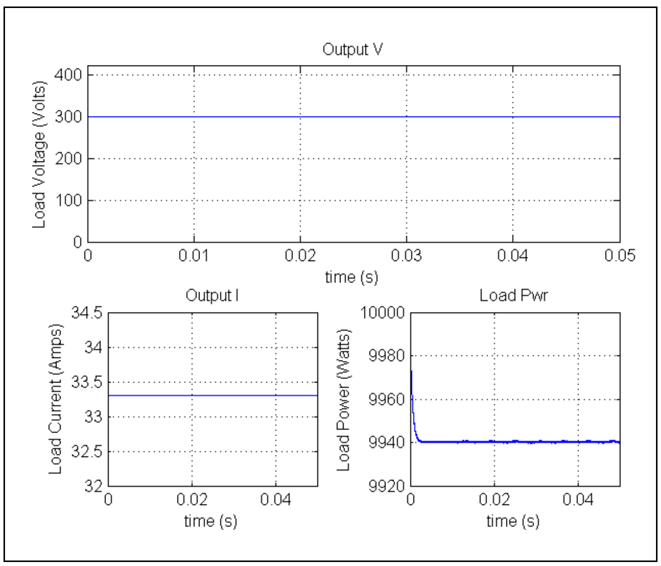

Figure 8: Closed loop PWM-RC simulation results.

A version of the presented PWM-RC control was implemented for a commercially produced PMSM generator. Testing was performed with a four-quadrant dynamometer as the source of mechanical power and a bidirectional dc power supply loading the regulated dc bus. Figure 9 is an oscilloscope plot showing startup and passive rectification of the system up to 800 RPM (idle). The PWM-RC is then turned on to being regulation of the 300VDC bus. This would simulate startup, then a command from the system controller to regulate the 300VDC bus.

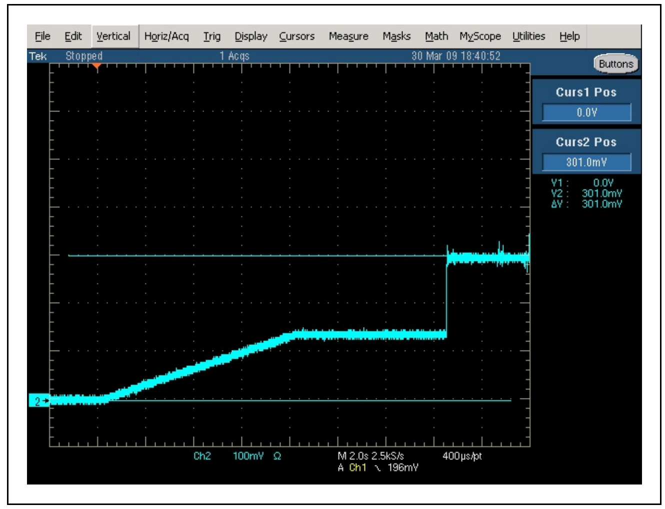

Figure 9: Vehicle startup simulated using the SIL.

Low Inductance Windings

When operated with PWM-RC control in a boosting region the achievable ratio between operating bus voltage and generator line voltage is independent of winding inductance in a practical sense. This independence is the result of closing a voltage loop around the converter bus capacitance with an inner current loop. The winding inductance does influence the control bandwidth and level of ripple in the bus current. Some systems may include generators with low winding inductance and require additional inductance to meet filtering requirements. The following is a discussion of the addition of inductance electrically in series with the windings, but external to the PMSM.

Insertion of the external phase inductance results in controller/converter terminal voltages no longer equivalent to generator terminal voltages when under load. This difference is attributable to the voltage drop across the external inductors. A per-phase equivalent circuit of the PMSM ISG is shown in figure 10.

In general, the external inductance L_{external} is seen by the controller as part of the plant. The ISG phase inductance L_ϕ is typically of the form

$$L_\phi = L_A - L_B \cos(2\theta). \qquad (19)$$

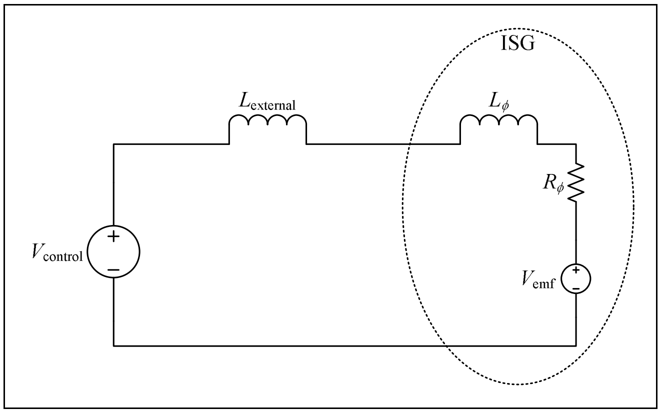

Figure 10: PMSM per-phase equivalent circuit.

Application of Kirchoff's voltage law shows

$$V_{\text{control}} = R_\phi I + j\omega\left(L_{\text{external}} + L_A - L_B \cos(2\theta)\right)I + V_{\text{emf}}, \tag{20}$$

where I is the phase current and θ is as previously defined. In terms of electrical dynamics the external inductance increases the "dc" portion of the circuit inductance without changing the portion dependent on rotor position. In general, the d and q axis inductances are equal to L_A plus/minus half of L_B, with L_q having the larger value. With addition of the external inductance the d and q axis inductances seen by the control system have increased equally with the difference between the two now a smaller percentage.

Field weakening is achieved by creating a magnetic field which interacts with the rotor's permanent field. The goal is to limit the voltage presented to the converter terminal, when field weakening during generation. This limiting is to prevent the overvoltage of components internal to the drive. The d axis current needed for a given level of field weakening is inversely proportional to the winding inductance. Only the inductance internal to the machine contributes to field production. External inductance does not contribute to weakening of the net magnetic field. However, the external inductors do contribute to the total voltage drop due to their impedance. The voltage presented to the converter is equal regardless of location of the inductors. Figure 11 show simulated ISG terminal voltages for two cases: 100% of inductance inside the machine and 20% internal with 80% external. In both cases the total inductance is equal.

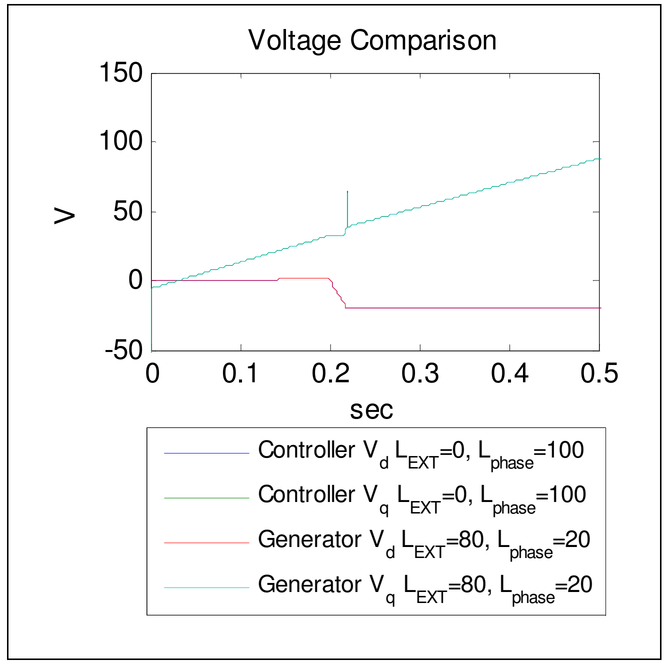

Figure 11: External inductance simulations.

DISCUSSIONS AND CONCLUSIONS

In this paper, three different (DFW, PWM-RC, and low winding inductance) aspects of system operation and control are considered. DFW is presented from the viewpoint of the equations and mechanisms governing system performance that might be manipulated to optimize system efficiency. By manipulation of the speed where the field weakening current begins to be introduced the output efficiency of the machine / drive combination is shifted. For the units tested the change resulted in a shift of the high efficiency region to higher speeds and higher torques with the addition of an increase in peak efficiency. The results would indicate that the higher speed option is appropriate for higher power operation. However, when output power is below the rated value for the generator, some efficiency improvements may be achieved by reducing the field weakening speed.

PWM-RC is discussed as a control technique capable of regulating the rectified output of an ISG without significant energy storage on the bus. Simulated and experimental results verified the technique capable of developing a tightly regulated operating bus voltage without significant energy storage (a battery pack) to buffer load transients. The control was shown to have sufficient bandwidth to maintain the operating voltage regulation under operation with load transients.

Finally, the impact of operating a low winding inductance permanent magnet synchronous machine above rated speed is investigated. Analysis and simulation showed the operation and control of the ISG is unaffected by the distribution of inductance internal and external to the machine. This independence allows the system designer to factor the distribution of inductance as an addition design parameter with the total inductance the prime consideration for electrical operation.

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